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THE DIAGNOSING OF TROUBLES IN ELECTRICAL MACHINES

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Edited by CHARLES P. SPARKS, M.Inst.C.E., M.I.E.E., Past President of the Institution of Electrical Engineers.

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LONDON, NEW YORK, BOMBAY, CALCUTTA, AND MADRAS.

THE DIAGNOSING OF TROUBLES IN ELECTRICAL MACHINES

BY

MILES WALKER, M.A., D.Sc., M.I.E.E.

PROFESSOR OF ELECTRICAL ENGINEERING IN THE FACULTY OF TECHNOLOGY IN THE UNIVERSITY OF MANCHESTER (MANCHESTER COLLEGE OF TECHNOLOGY)
CONSULTING DESIGNER TO THE METROPOLITAN-VICKERS ELECTRICAL COMPANY, LTD.

WITH ILLUSTRATIONS

LONGMANS, GREEN AND CO.
39 PATERNOSTER ROW, LONDON
FOURTH AVENUE & 30TH STREET, NEW YORK
BOMBAY, CALCUTTA, AND MADRAS
1921

PREFACE

During the last thirty years a large number of troubles in connection with electrical machinery have come to the notice of the author, and in some cases he has been puzzled to find out what was wrong. It is thought that if the experience gained during these years can be recorded in some kind of logical order, so as to be easily available to engineers when dealing with similar troubles, the record will not be without interest, and in some cases will throw light upon a difficulty. It is impossible for the author to deal with all the troubles that can occur in dynamos. The accidents that can happen and the mistakes that can be made are so diverse and numerous, and the ways in which a defect in the machine can hide itself are so perplexing, that one can only hope to deal with a small percentage of the troubles and to indicate the general methods of attacking problems of the kind. It is hoped that readers who have found other troubles, methods of diagnosis, and ways of curing defects, that are not given in this book, will communicate them to the author, so that a future edition of this book may be of greater service to the electrical industry. It is only by the co-operation of a large number of dynamo testers, erectors, designers, and trouble engineers that a really good collection of diseases and cures can be compiled.

These co-workers will agree in the following advice to all investigators of troubles in dynamos:

First find out the facts; see the thing yourself; let your conclusions be drawn from ascertained data and not from supposition. After the facts have been clearly stated and the necessary conclusions drawn, a happening that was very elusive in the telling may be very simple in the seeing.

The investigator's difficulty often arises from his neglecting to take a measurement which is the key of the situation. For this

reason it is a good plan to make a list of all the possible causes of the trouble in question, looked at purely from a theoretical point of view. Each possible cause, when written down will suggest measurements that might be taken to investigate it; and a broad view of possible explanations leads us away from the narrow track of thought into which a preconceived opinion has led us. Sometimes a theoretically possible cause of trouble, written down more in fairness to a complete statement than from its own inherent probability, may point to an omission in our data which, when rectified, makes everything clear.

The Author wishes to acknowledge the assistance he has received from the many testing and erecting engineers with whom he has worked. He wishes to thank Mr. David Isaacs for his careful reading of the proofs and the preparation of the Index, and also the Editor of the *Electrician* for permission to use Fig. 302, p. 351, "Connections of Double Brush for Automatic Adjustment of Commutating Pole."

MANCHESTER, *June* 1921.

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INTRODUCTION.

THE circumstances under which an engineer has to deal with troubles in electrical machinery fall into two main classes. There is the case where a machine has already been in service and operating satisfactorily until some mishap brings about the trouble to be investigated, and there is the case where a machine gives trouble from the first day it is run. It is clear that where the machine has already proved to be of sound design and, upon the whole, of correct construction, the investigations to be made are of a simpler nature than in the case where the investigator may be led to check every element in the construction, and even to question the validity of the design itself.

Cases of the first class must often be dealt with on the user's premises, the mill, the mine or the sub-station where no special facilities are available for making tests, and as often as not the engineer who is hurriedly called to find the trouble has had no opportunity of ascertaining beforehand what instruments he will need or what kind of investigation is before him. It will be convenient to speak of these as "out-door" cases, to distinguish them from "works" cases where every facility is at hand to make a test, and where the machine can be run or stopped at will.

In dealing with the various ailments and defects in machines we are more especially concerned with "out-door" cases, but it will be convenient to consider some of the most important "works" tests directed to discover inherent defects in the machines under consideration. It is not within the province of this book to deal with the routine of dynamo testing. There are already several excellent books which deal with the latter subject.

EQUIPMENT.

Equipment for "outdoor" cases: The engineer who is hurriedly called away had better not try to take with him everything that he may possibly want. He must rather, by the exercise of discretion

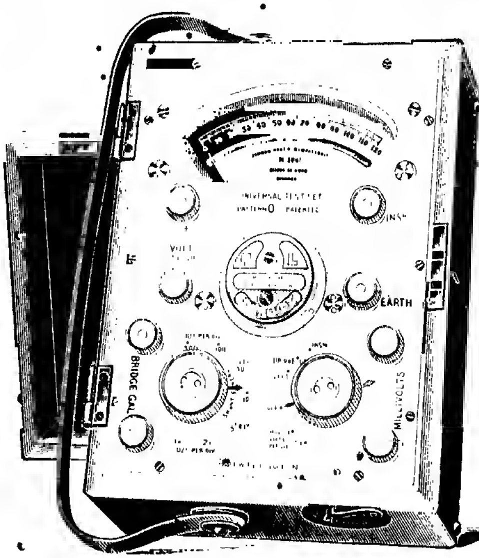


FIG. 1.—Universal Testing Set made by The Cambridge and Paul Scientific Inst. Co.

and foresight, confine his equipment to articles that are most likely to be wanted, having regard to the nature of the trouble as reported.

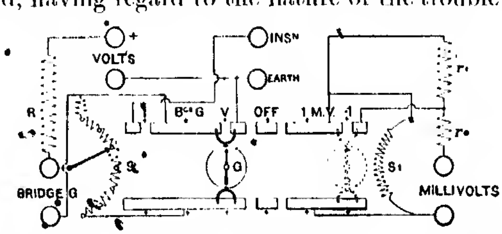


FIG. 2.—System of connections of R. W. Paul's Universal Testing Set.

The following instruments and pieces of apparatus have been found useful in numerous instances, and should be at hand so that they can be taken in suitable cases :

(1) **A Universal Testing Set** for measuring continuous currents and voltages over a wide range, say, from 1 micro-ampere to 600 amperes and from 0·1 of a milli-volt to 600 volts. Fig. 1 illustrates such an instrument made by The Cambridge and Paul Scientific

Instrument Co., which is very convenient and reliable. The scheme of internal connections is illustrated in Fig. 2. The instrument can also be used as a bridge galvanometer having a sensitivity of two scale-divisions per micro-ampere.

(2) **An Alternating Current Voltmeter**, having the scales to 150 and 600 volts respectively. Such an instrument made by The Weston Electrical Instrument Co. is illustrated in Fig. 3. It is also well to have a low-reading A.C. voltmeter reading up to about 1·5 volts. An **Alternating Current Ammeter** to be used in conjunction with series transformer will sometimes be needed for "out-door" cases.

FIG. 3.—Weston A.C. Voltmeter.

(3) **An Alternating Current Wattmeter** designed to take 100 or 500 volts and reading up to 5000 watts, see Fig. 4. The range of this wattmeter can, of course, be extended up to any amount by means of voltmeter transformers and series transformers.

FIG. 4.—Weston A.C. Wattmeter.

(4) **An Ohm-meter** for taking direct measurements of insulation resistance and other resistances. Fig. 5 shows an instrument made by Everett, Edgcumbe & Co. Ltd., having five ranges. The same firm makes an instrument having eight ranges which will measure accurately any resistance from 0·1 of an ohm to 50 megohms. This is a most useful instrument for the tester to have at hand.

Another instrument widely used by the tester is the "Megger," made by Messrs. Evershed & Vignoles. It is made for the following ranges expressed in megohms: 0-10; 0-20; 0-100; 0-200; 5-1000; 10-2000; 15-5000. By the addition of certain parts it may be used

for measuring low resistances. This combination is known as a "Bridge Megger."

FIG. 5.—Ohm-meter made by Everett, Edgcumbe & Co. Ltd.

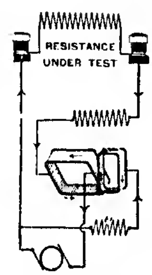


FIG. 5A.—Connections of Ohm-meter.

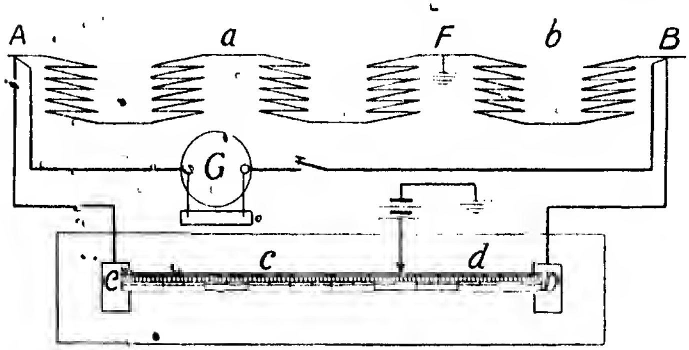


FIG. 6.—Metre bridge arranged to find a fault in a field circuit.

(5) **A metre of German-silver wire** mounted on a board with suitable sliding contact to be used as the variable arms of a Wheatstone bridge. It is convenient for some purposes to arrange the

mounting so that the last two centimetres at each end of the wire can be short-circuited, and so that two copper flexible cables, of the same resistance as the short lengths of German-silver wire thus cut out, can be used as connecting cables. These two cables are shown diagrammatically at AC and BD in Fig. 6. This plan enables the bridge to be connected to any part of a dynamo and direct readings to be taken of resistance ratios without making any correction for

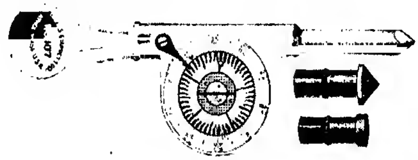


FIG. 7.—Revolution counter made by L. S. Starrat Co.

the resistance of the cables. If, in taking a reading, it is found that the slider comes too near one end, say, end B in Fig. 6, the opposite end A is disconnected from the end of the winding that is being tested and reconnected to a point in the winding much nearer to B. This process can be repeated until a reading is obtained near the centre of the scale or it appears that the resistance in the B branch is zero.

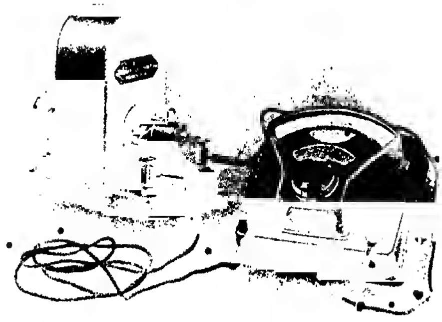


FIG. 8.—Portable tachometer made by the Weston Electrical Instrument Co.

(6) **A Revolution counter and a Tachometer.** Speed counters fall into two classes: (1) the revolution counter such as is illustrated in Fig. 7; (2) the direct-reading speed counter in which a pointer moving over a scale gives an indication of the speed at any instant. As the revolution counter is much more portable, it is the one which is most generally used by engineers. There are cases, however, when it is necessary to know the instantaneous speed. In these cases, a tachometer such as that illustrated in Fig. 8 is convenient.

On page 77 the **Stroboscopic Method** of measuring speed is described. For many purposes this method is more convenient than a tachometer.

(7) **Resistance and Voltmeter points**: These constitute what is sometimes called a "**lighting-out set.**" It may conveniently consist of two lamp-holders connected in series, designed to take either 110 or 250 volt incandescent lamps (see Fig. 9). These are connected at one side to flexible cable, say 10 yards in length, sufficient to stretch to the positive terminal $T+$ of the power supply, and connected at the other side to a steel point $P+$ attached to an insulating handle. Another steel point $P-$ is provided with sufficient cable to stretch to the negative terminal $T-$ of the supply.

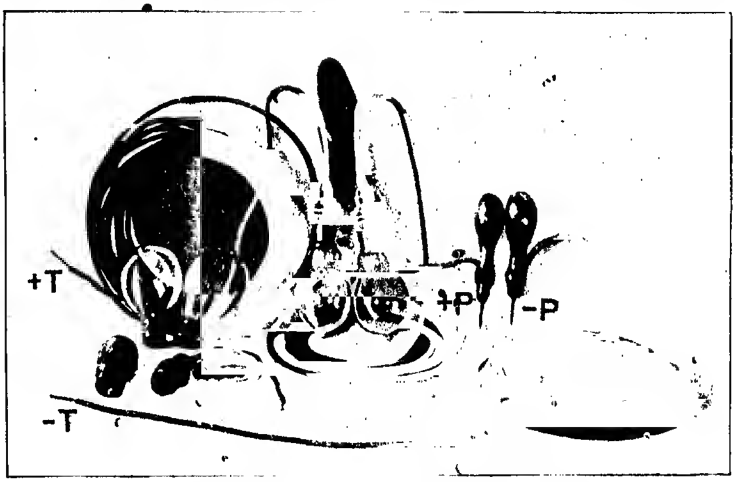


FIG. 9.—" Lighting-out set " adapted for a variety of tests.

It is convenient to have two voltmeter wires connected to a lamp-top designed to fit into the bayonet-socket lamp-holders, so that a voltmeter can be connected instead of a lamp. Another short-circuited lamp-top may be provided for use when only one lamp is in circuit.

(8) **Portable Accumulator** capable of giving 20 amperes at 6 volts for one hour.

(9) **A Compass Needle** pivoted so that it can work in any plane. See Fig. 9A.

(10) **A Non-magnetic Stop-watch.**

(11) **A Slide Rule.**

(12) **Thermometers.**

(13) **Thermo-couples** arranged to be used in conjunction with a milli-voltmeter. These may be made of iron and eureka wire,

and calibrated in an oil bath. An iron-eureka junction at ordinary temperature gives an E.M.F. of about 57 micro-volts per degree Centigrade difference of temperature between hot and cold junctions. The calibration curve is almost a straight line.

(14) **A Telephone** which can be connected to two coils arranged as an induction balance (see Fig. 10). A suitable exciting circuit can be made up from a four-volt battery a resistance of 0·5 ohm, a rough file and an ordinary bradawl with which to scrape upon the file (see pages 21 and 32).

(15) Several **Frequency Meters,** each giving direct readings over an open scale on both sides of a standard frequency. The instrument illustrated in Fig. 10A is suitable for 25 cycles.

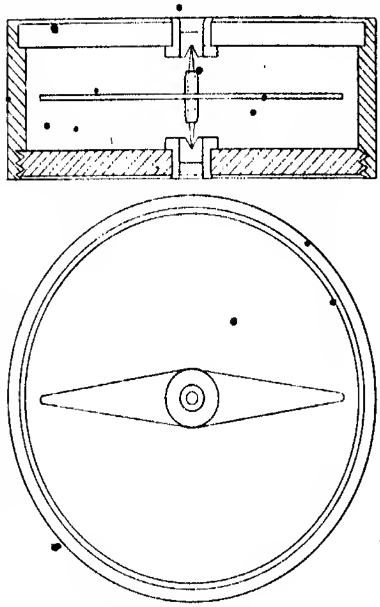


FIG. 9A.—Compass needle mounted to swing in any position.

(16) **A Phase-rotation Indicator**, such as that illustrated

FIG. 10.—Simple arrangement of induction balance for detecting the position of faults.

in Fig. 10B. The clips attached to this instrument can be readily clipped on to the terminals of a low voltage 3-phase

circuit and the instrument gives at once the rotation of the phases.*

(17) **A Hand Lamp** with guard cage will be useful in dark situations when no other portable lights are available.

(18) **Set of Trammels** or big dividers having a span of 15″ or 18″ provided with a lock for fixing very positively the distance between the points, and also provided with a fine screw adjustment.

(19) **A Box of Coloured Chalks.** White, green, blue, and red.

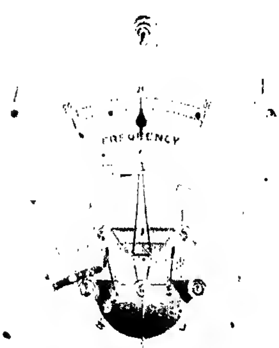


FIG. 10A.—Frequency meter made by the Weston Elec. Inst. Co.

FIG. 10B.—Phase-rotation indicator made by Everett, Edgcumbe & Co.

In addition to these, various measuring instruments will be required in special cases. These will be referred to later as the cases arise.

For commutation work, special apparatus such as that described on p. 282 may be required.

Whenever possible the engineer should take away with him copies of any curves that give the results of tests taken on the machine in question. If these are not available, he should get from the designer particulars of the resistances of the various parts, the

* See Dr. Gisbert Kapp on "The Determination of the Sequence of Phases from Wattmeter Readings," *Jour. Inst. Elec. Engrs.* vol. 55, p. 309.

normal exciting current and such other data as may appear useful
Much time is often saved by having these data at hand.

In cases of difficulty it is a good plan to have a chat with th
designer, who may know something of the idiosyncrasies of th
machine.

GENERAL SCHEME OF THIS BOOK.

It will be convenient to begin with the consideration of trouble
that are common to all classes of dynamo-electric machinery, and
after having disposed of these in a few preliminary chapters, t
consider the ills that are peculiar to various kinds of machines i
chapters assigned to the kinds of machine in question.

CHAPTER I.

BREAKDOWN OF INSULATION.

FAULT TO EARTH.

SOMETIMES there is a clear indication of a fault to earth, and sometimes there is only a suspicion of an intermittent fault to earth when the machine is in operation.

Permanent fault to earth.

In cases where an inspection of the machine fails to reveal the position of the fault, the first step is to find its position by some electrical or magnetic means. Two classes of methods are in common use: (1) Bridge methods, and (2) "Direction of flow" methods. To these may be added (3) "induction-balance" methods employing an alternating current and a telephone.

Bridge methods of finding a fault to earth.

If we are dealing with a circuit on a machine which has only two ends, such as an ordinary field circuit, we may make the connections as shown in Fig. 6. In this figure, six coils of a field circuit are shown, the two ends being at A and B. The cables from a metre wire CD are connected to the terminals A and B, to which are also connected terminals of a galvanometer G. One of the terminals of an accumulator or other battery is connected to the framework of the machine, which in this case represents earth, and after the galvanometer has been shunted, the other terminal is connected to the roving point on the metre bridge. Contact is made with the metre wire in the ordinary way, the galvanometer key depressed to see if there is any deflection, and the roving point moved along CD until a position is found at which no deflection of the galvanometer occurs when the key is depressed. Then, taking the ratios of the resistances, we have $\frac{c}{d}=\frac{a}{b}$, where a is the resistance of AF and b is the resistance of BF, F being the position of the fault.

If, as in Fig. 6, the length of *c* is twice the length of *d*, the earth in the field circuit is most probably near the point indicated, a breakdown most commonly occurring near the terminals. The branch *a* contains four field coils and the branch *b* two field coils. This is on the assumption that all coils and the connections between them have the same resistance, and all coils are in circuit. If any of the coils are wholly or partially short-circuited (there being, say, two faults to earth), or if the resistance of the joints in the field circuits is unduly high, the fault may be at a point other than that indicated in Fig. 6.

If the above test does not lead at once to the discovery of the fault, as, for instance, where it indicates that the fault is somewhere inside one of the coils, the next step is to disconnect the wires of the bridge and galvanometer at the point *A* and move them to a point nearer to *F* but still on the same side of *F*. A new point of balance having been obtained on the bridge, and the position of *F* being now more definitely ascertained, the bridge wire and galvanometer wire are moved from *B* up to a point nearer to *F* but still on the same side of it. This will, in general, bring the terminals of the bridge and galvanometer to the two terminals of a coil, and when the balance is obtained upon the bridge, we have a pretty clear indication as to how far from one of the terminals of the coil the fault exists.

Direction of current method.

This method is based on the simple fact that if an electric current is fed into a conductor at both ends, and drawn out at any intermediate point, that point can be detected as we pass along the conductor, because it is the point at which the direction of the current is reversed. Let current be fed into the conductor *AB* at *A* and *B*, and let it escape to earth at *F*, as in Fig. 11. Suppose we have some means of detecting the direction of the current at any point along the wire, and that we make observations at successive points. Beginning at *A* we observe that the current at first flows from *A* towards *F*, but as soon as we pass *F* the direction of the current changes. Thus the point *F* is indicated although it may be

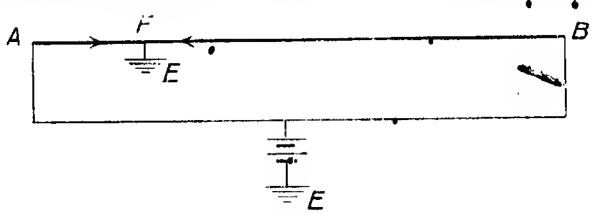


FIG. 11.

hidden from view by the structure of the machine. There are two common ways of ascertaining the direction of current at any point of the conductor: (1) by the magnetic effect, (2) by drop in electric potential. When a milli-voltmeter is available, the drop-in-potential method will be found the most convenient: but in the absence of a suitable voltmeter the magnetic method may be useful. Where the conductor is of fairly simple form, as where it is part of the armature winding of a low voltage generator built up of bars embedded in slots connected by copper end connectors, it is possible to observe the magnetic effect by means of a compass needle held over the slots.

The magnetic method.

In making use of the magnetic field around an armature to find the position of a fault in the insulation of the conductors, two stages

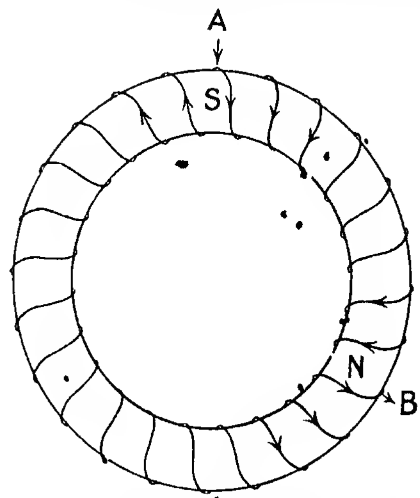


FIG. 12.—Showing how in a gramme ring a pole is produced near the point where the current escapes at a fault.

in the enquiry can be differentiated. We may investigate (*a*) the distribution of the field around the armature as a whole, (*b*) the local distribution in the immediate vicinity of the slots. For both stages the best plan is to pass current from the conductors through the fault to the frame, so that the flow of current in the conductors may be such as to produce a distribution of magnetic field so distinctive in its character as to indicate the position of the fault. In stage (*a*) the main principle made use of is, that when a current is led into and out of an armature winding like that of a D.C. armature, magnetic poles are produced at the points where the

current enters and leaves the armature. The simplest case to consider is an ordinary **ring-wound armature**, as shown in Fig. 12. It is seen that if current is fed in at A and out at B, poles are produced at A and B. If we have a fault to earth at B whose position is unknown, we can pass current into the conductors at any point A and obtain a return circuit through the iron, the fault acting as the point B in Fig. 12. If we are dealing with a ring-wound armature and passing an ascertained current, say 10 amperes, it will be found that the nearer the point A is moved to the point diametrically opposite to the point B, the stronger the magnetic field will be. If A and B coincide, no poles are produced on the armature.

If, however, as is more usually the case, we are dealing with a **drum-wound armature**, which is wound for a definite number of poles, and therefore has a definite coil span, it will be found that the position of A relative to B, which gives the strongest magnetic field, is exactly the throw of a coil away from B. If A is put at a point some distance from B on a multi-polar machine, a pole will be produced at B, and a pole of opposite sign on each side of B; but no increase in the strength of these poles is produced by increasing the distance between A and B by more than the throw of a coil. When dealing with a multi-polar D.C. drum-wound armature, the procedure by method (a) is to feed in current at any commutator bar and take it out from the spider, and then search around the armature by means of the double-pivoted compass needle for a well-defined pole of opposite polarity to the pole produced by A. When this has been roughly located, we should remove the position of A until it is the throw of a coil away from the supposed position of the fault. It will now be found that the position of the pole is more clearly defined, and we may proceed by method (b) to get at the position of the fault more exactly.

If we turn the armature round in its bearings so that the fault is at or near the top, and hold the double-pivoted compass needle (Fig. 10) so that it can swing in a vertical plane and at a distance of about 6″ from the armature, we shall find that the magnetic lines from the pole in question are at that point almost vertical and at a greater distance curve round to the pole of opposite sign forming what we have called the general field around the armature. If we now lay the compass down on the working face of the armature with the pivoted axis vertical so that the needle can only swing in a horizontal plane, we shall find that in addition to the general field around the armature there is a local field extending from tooth to tooth, and the compass needle in this position, if only separated from the armature by a piece of fuller board a millimetre thick to give it a level surface to stand on, will be controlled in its movements

almost entirely by this local field. The direction in which the *N*-seeking end of the needle points from tooth to tooth is now an indication of the direction of the algebraical sum of all the currents in the slot immediately beneath it. To make the indications positive it is best to put the pivot of the needle directly over the centre line of the slot and turn the armature round on its bearings until the slot in question is uppermost on the armature. We then apply the rule for the direction of magnetic field around a conductor carrying current. The direction of the magnetic field around any conductor carrying a current is easily found by grasping the conductor (or imagining the conductor to be grasped) in the right hand with the thumb pointing in the direction of the current, then the way that the fingers point around the conductor is the way that a *N*-seeking pole will travel. Thus, if we place a compass needle over a conductor in which the current is going away from us, the *N*-seeking pole will point to our right, but if the needle is below the conductor, the *N* pole will point to our left. If each slot only contained one conductor, the finding of the fault by this method would be extremely easy, because it would only be necessary to pass from point to point over the slots until we came to a place where the direction of the needle reversed, and that would at once indicate the position of the fault. D.C. machines, however, are usually wound with two coil sides per slot, and most commonly contain several conductors on each coil side, so that the indications are not as marked as they would be if we were only dealing with one conductor.

Simplification of current distribution. In order to make the indications as positive as possible it is as well to proceed as follows:

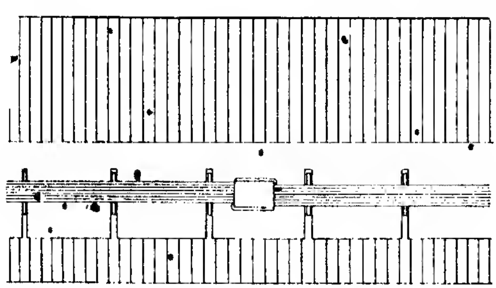


FIG. 13.—Showing method of short-circuiting cross connectors on a D.C. armature.

Find out from inspection or by reference to the design records, which commutator bars are connected to equalising rings. Connect all these bars together electrically. This can conveniently be done by fitting over the commutator a sleeve of thick paper in which slits have been cut to lie opposite the bars in question (see Fig. 13), then after having wrapped a band of bare copper wire of two or three

turns round the commutator, push some pieces of reasonably thick copper wire between the commutator bars in question and the copper band so as to make electrical connection between them, and tighten up the band until it grips these pieces firmly. We now pass current into this copper band and out from the spider of the armature. The state of affairs will be easily understood by reference to Fig. 14, which shows a part of the development of a C.C. drum-wound armature having 12 slots per pole and a coil throw of 1 and 12. Thus it is

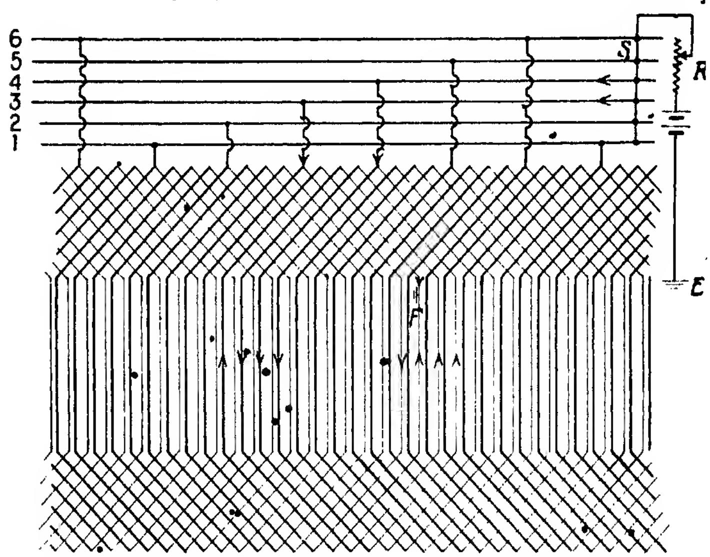


FIG. 14.—Showing method of passing current from all connector rings through part of the winding to a fault.

short-chorded by one slot pitch. Fig. 14 shows the armature coils as though each contained only one turn. This is convenient for the first step in the argument and for showing the general distribution of current in the armature coils as a whole. After illustrating this we will pass on to Fig. 15, which shows coils containing 3 turns per coil (making 6 conductors per slot), and from a figure of this kind we can study more exactly how the current is distributed in all the conductors lying in one slot. Fig. 14 shows the six cross-connecting rings short-circuited at *S*, and the conductor connected to the frame at *E* carried to a battery and through a regulating resistance *R* to *S*. If now we have a fault *F*, it will be seen that current will flow from *E* through *R* and *S* to the cross-connecting rings, but as these are all at the same potential, the only rings that will carry current will be those numbered 3 and 4. The current which passes from

the armature winding to F passes along the conductors as indicated by the arrow-heads in the figure. The main object of short-circuiting all the cross-connecting rings is to reduce them to the same potential, so that no other currents pass in the armature than those indicated by the arrow-heads. If we were to pass current into the armature winding at only one point, we should have an exceedingly complicated current distribution, because there would be many paths, each having its own resistance, by which some current could find its way to F. *In Fig. 14 the thick lines represent the coil sides lying in the upper part of the slots, and the thin lines coil sides in the lower part.* We have shown the fault in a lower conductor, but the same argument would apply if it were in an upper conductor. It will be seen that by reason of the short-circuiting of the cross-connecting rings there are only two bands of conductors carrying current—an upper band on the left and a lower band on the right. Thus there is no magnetic effect from the upper conductors on the right, and we can leave them out of account. The most usual place in the slot for a fault to occur is at or near the end of the armature iron. If there is only one conductor per coil side, we see from Fig. 14 that it can be quite easily located by the compass needle indications without interfering with the insulation of the armature, and its position may then be very positively ascertained by the drop in potential method described on page 18. We now come to the case where there are a number of conductors per coil side, say 3, as in Fig. 15. This figure is drawn on the assumption that the commutator is on the lower side of the figure and the cross-connectors on the opposite side. For simplicity, only a few of the coils are shown, and the scale has been somewhat distorted in order to open out the conductors at the parts under consideration. It will be seen, however, that the general distribution of current taken in the coils as a whole will be the same as in Fig. 14: that is to say, the short-circuiting of the connecting rings will bring about a distribution which gives us only two bands of conductors carrying current, namely, a band of upper conductors on the left (only some of which are shown) and a band of lower conductors in the middle of the figure, the main point being that there is no current in the upper conductors in the middle of the figure. By exploring with a compass needle in the vicinity of the magnetised teeth and by making a diagram of the directions in which the current flows in each coil, there is very little difficulty in ascertaining the position of the fault, the rule being that the current flows from two cross-connecting points nearest to the fault along the conductors through the fault to earth. The current distribution shown in Figs. 14 and 15 can be employed in finding the position of a fault by the drop in potential method described on page 19.

Three-phase winding. In finding a fault on a 3-phase star connected winding by means of the compass needle, the best plan is to connect all the outer terminals together and connect these to the star point, and then to pass current from this common junction through the fault to earth. In this way the current passes through one phase only and makes the indications much simpler than if some current is passing in all the phases. On a mesh-connected armature it is only necessary to connect all three terminals together and pass the current from these terminals through the fault to earth.

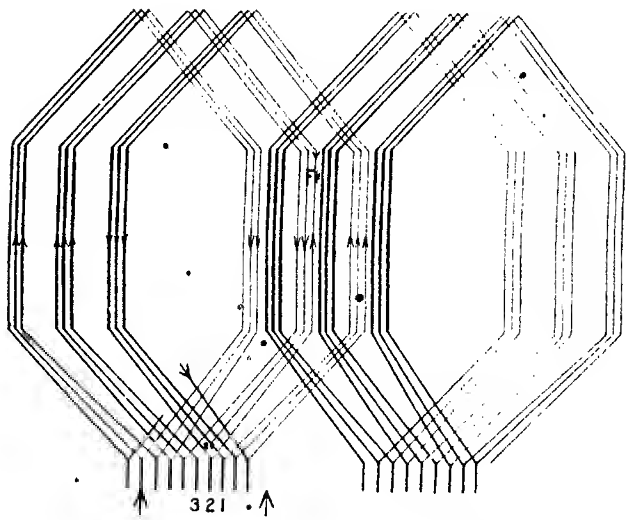


FIG. 15. Showing the path of current through a D.C. armature winding to a fault at *F*.

Measure of the strength of the field. In some cases position of the fault is only indicated by a change in the strength of the magnetic field. These cases are best attacked by other methods, such as the bridge method, page 10; but it is sometimes possible to get a very certain indication of the position of the fault by roughly measuring the strength of the magnetic field across the top of the slots in the following way: Put the compass needle near the point where the fault is suspected, so that its pivot is directly opposite the centre line of the slot and at a definite distance from the mouth of the slot. Allow the needle to swing on its pivot and by means of a stop-watch note roughly the time taken to make five swings. Now put the needle down a little further along the slot with its pivot opposite the centre line as before, and at the same distance from the mouth of the slot. Again take the time of five swings.

If it is the same as before, move to a further point, and so on. As soon as you pass a point where a considerable fraction of the current in the slot is going to earth, a change in the time of five swings will be noticed. The periodic time of swing varies inversely as the square root of the strength of the field. The strength of the field across the mouth of the slot depends upon the strength and direction of the current in each conductor. Suppose that there are two conductors per slot, and that the fault to earth is in one of them,

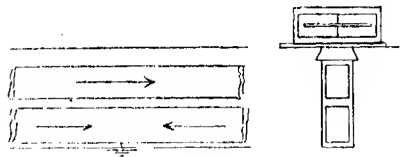


FIG. 16.

so that the current flows as indicated in Fig. 16. At one side of the fault the magnetic effects of the currents are added and at the other they are subtracted. We shall not, in general, find that the magnetic field is zero over the part of the slot where the currents are subtracted, because the current going into the fault is not, in general, equally divided between the conductor to the right and the conductor to the left, moreover, the magnetic effect of conductors in the vicinity always produces a field which affects the compass needle to a certain extent. Nevertheless, when there are only two conductors per slot, the difference in the movement of the needle is usually so marked as to clearly indicate the position of the break in the insulation. If there are four conductors per slot with the current flowing as indicated

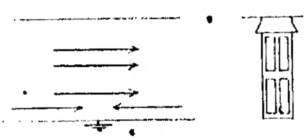


FIG. 17.

in Fig. 17, the field to the left of the fault will be twice as strong as the field to the right. The compass needle will take 1·41 times as long to make five swings on the right side as it takes on the left side, and this will be sufficient to indicate that the fault is there.

Drop in potential method.

One of the most accurate ways of finding the direction of flow of a current in a conductor is by bringing into contact with it two voltmeter points as shown in Fig. 19, and noting the direction of the voltage between them. This can conveniently be carried out by means of the apparatus shown in Fig. 9. The measurement of

the drop in a conductor of known length and size has a great advantage over the magnetic method in that it is much more exact quantitatively.

In dealing with a **lap-wound armature** having a great number of circuits in parallel cross-connected in the usual manner, it is not necessary to go to the trouble of short-circuiting the cross-connected points, because, although the distribution of current in the armature is exceedingly complex when we feed the current into the winding at one bar of the commutator and take it out at the fault, the fact that we have an exact quantitative method of measuring the drop between the consecutive bars and the commutator enables us to find the position of the fault fairly easily. The principle to be made use of is as follows: If the current is fed into a bar which is connected to the winding at a point diametrically opposite the fault, it would divide equally between the parallel paths from the point in question to the fault. If, on the other hand, it is fed into a point of the winding near the fault, most of the current will go by the short path from the feeding-in point to the fault, while each of the other paths will carry a smaller current. We must further remember that the cross connectors tend to equalise the potential of all points to which they are connected; so that when the current is fed into the winding at a point almost diametrically opposite to the fault the cross connectors will short-circuit most of the armature winding proper between the region of the feeding-in point and the region of the fault. We shall therefore find that in the vicinity of the feeding-in point and the fault the drop in potential between consecutive bars on the commutator is very much greater than in the regions in between. The plan, therefore, is to feed current into the winding at any commutator bar connected to a cross-connecting ring and take it out at the fault. Maintain this current constant. After shunting the galvanometer, measure the drop in potentia between consecutive bars at various points around the commutator. The armature detector made by Everett, Edgcumbe & Co. Ltd., and illustrated in Fig. 18, is very useful for this purpose because it is protected by means of a resistance which can be cut out when only a small deflection is obtained, and is thus not so liable to be burnt out. It will be found that at one region of the commutator the drops between bars are much higher than at other parts. This is in the vicinity of the fault. Keeping one voltmeter point in the right

FIG. 18.—Low reading voltmeter with protecting resistance, by Everett, Edgcumbe & Co. Ltd.

hand and the other in the left, bring them down on two consecutive bars and notice whether the drop in potential is positive or negative; then pass to the next two consecutive bars, still keeping the left to the left and the right to the right and again notice the polarity. Continue this process until the potential reverses at a certain pair of bars. The fault is then in a conductor connected to the bar which is common to the last two readings. Thus referring to Fig. 15, commutator bars to the right of bar 1 are higher in potential than bar 1 and *bars to the left of 3 are higher than 3. As we pass from 1 and 2 to 2 and 3 the reversal occurs. Thus the fault* is in a conductor connected to 2. If the reading obtained between bars Nos. 0 and 1 be taken as unity, and if we denote by d the fraction of this reading obtained between bars 2 and 3, it will be found that the fault lies at a point $\frac{1}{2}(1-d)$ of the section of the winding away from bar No. 3. Thus, if the reading is zero, then the fault lies half-way between 2 and 3. If the reading is $-\frac{1}{2}$ the fault lies $\frac{3}{4}$ of the section away from bar No. 3. It will be found that with a sensitive galvanometer, such as that used with the universal set, Fig. 1, it is possible to get an indication of the direction of difference of potential even when the difference is only ·01 of a milli-volt, so that if 10 amperes is being passed through the conductor, one can measure the drop in potential in a short length having a resistance as small as a micro-ohm. This enables us to measure the drop in potential in an exceedingly short length of conductor. Having found the approximate position of the fault by observations on the drop in potential between bars, we can proceed to take the drop in a short length of an individual conductor in the armature either by pricking through the insulation of the conductor or, where our apparatus is sufficiently sensitive, by making use of the short length of bare conductor which is usually found near the commutator neck as illustrated in Fig. 19. If, for instance, the armature conductor has a cross section of 0·1 sq. cm. it will have a resistance of 17 micro-ohms per cm., so that the drop in 0·5 cm. when 10 amperes is passing will be about 85 micro-volts; and this is quite sufficient to give an indication on a sensitive galvanometer. Referring now to Fig. 15, we see that if current is fed in at any part of the winding and taken out at the fault F, commutator bar No. 1 is at a higher potential than commutator bar No. 2, while com-

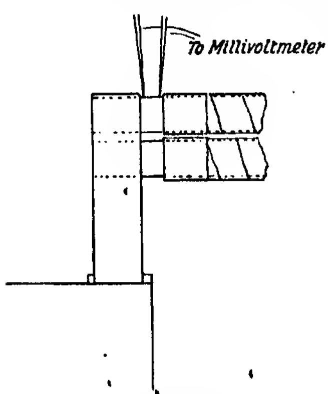


FIG. 19.—Method of tracing through the direction of current in a D.C. armature.

mutator bar No. 2 is at a lower potential than commutator bar No. 3. We therefore arrive at the conclusion that the fault is in a conductor attached to commutator bar No. 2. Apply now the voltmeter points to the ends of the conductor marked F, and we shall definitely find that the current is flowing in from bar No. 2 towards F, and in through bar No. 3 towards F. If we now prick through the insulator at the opposite end of the armature, we shall find definitely that the fault is in the half coil lying in the bottom of the slot.

When current is fed into any point of a **two-circuit armature** winding and led out at the fault it finds only two paths through the armature. On the shorter of these two paths the drop in potential between commutator bars is greater than on the longer. This in itself gives a rough indication of the position of the fault relatively to the feeding-in point. The method of finding the exact position of the fault is the same as with a lap-winding.

Another very simple method, which has been pointed out by Mr. E. B. Moullin, is to pass current from any commutator bar through the fault to the frame. Then connect one terminal of a millivoltmeter (suitably protected) to the frame, and take readings of the instrument when the other terminal is connected to various bars of the commutator. The bar which gives the lowest reading is nearest the fault. We are able to judge more exactly the position of the fault by taking the two lowest readings and judging from them how far along the winding lying between the two bars concerned the fault lies. This method is applicable when the resistance of the fault is very low as compared with the resistance of a section of the winding.

The drop in potential method can conveniently be used in finding a fault on any **open circuit winding** such as a 3-phase armature winding or a field circuit. All that is necessary is to pass current from one terminal through the fault and trace the current along successive conductors until a conductor is found in which no current is passing. It is then clear that the fault lies between this point and the last place at which a reading was taken.

Induction Balance Method. A telephone can be used in a great variety of ways for finding a fault. A very convenient apparatus is that depicted in Fig. 10. Two small coils of fine wire (giving a combined resistance comparable with that of the telephone) are wound on wooden rectangular bobbins of a size convenient to lay across the mouth of an armature slot. The two coils are rigidly fixed to a strip of wood and connected up so that when they are placed in a parallel uniform alternating magnetic field the E.M.F.'s generated in the coils just balance one another and no sound is heard in the telephone. An alternating current of high frequency is passed through the armature winding to the fault, and the two

coils are placed near the mouth of the slot in a symmetrical position so that when the same current is passing under each coil the telephone is silent or almost silent. By moving the coils about one can easily see whether the instant of silence corresponds to a position of symmetry. If now the coils are moved along the slot until one is on one side of a fault and the other on the other side, it is found that the telephone is not at all silent when the coils are in a symmetrical position with regard to the slot. A current of from 5 to 10 amperes, broken intermittently by scraping the point of a bradawl on a file, when passed through the winding to earth gives very clear indications in the telephone. The man working the bradawl must not be too near the man with the telephone.

FAULT TO EARTH OF HIGH RESISTANCE.

A high resistance fault to earth may be due to a defect in insulation at one point or there may be a general dampness of insulation extending over a considerable region. Dampness of insulation will be dealt with in the next section. Where a fault has a high resistance some testers advocate the breaking down of the resistance by the application of a high voltage. While this course may have to be adopted in certain cases, one should, as a general rule, try to find the position of the fault without breaking it down; because any attempt to do so may possibly have the opposite effect and make the resistance so high that the position of the break in the insulation may be difficult to determine.

The **bridge method**, p. 10, is the best method for finding the position of a high-resistance fault. It can always be applied in an open circuit winding. In a closed circuit winding, such as is found on a D.C. armature, greater difficulty arises. Where the armature has a two-circuit winding, the best plan is to open the circuit at one point by unsweating the conductors from one of the commutator necks and then to deal with it as an open circuit winding. When a high-resistance fault occurs on a lap-wound D.C. armature having a large number of cross connectors, we may distinguish between cases where the resistance of the fault is of the order of 20 ohms or lower and cases where the fault is of much higher resistance. A fault of 20 ohms or thereabouts will usually carry a current of 0·1 of an ampere without burning itself out and this current will be great enough to enable us to apply the methods of localising described on p. 18. When only a very small current can be passed through the fault, we may take as our index of direction of flow the drop in several turns of the armature instead of the drop in only one turn. This may not enable us to give the exact position of the fault but will lead us to locate it within fairly narrow limits. It will then be

possible to unsweat some of the conductors from the commutator necks, thus isolating the region in which the fault occurs and enabling us to apply the bridge method.

Where the resistance of the fault is so high that sufficient current cannot be passed through it to enable any of the above methods to be employed, the best plan is to break the armature up into two parts, find out which part the fault is in, then break that part up into two and so on until the section is sufficiently small to enable the bridge method to be applied with certainty.

Heating method of finding position of fault. This method is considered under the next heading, as it is mainly of service in dealing with intermittent faults.

INTERMITTENT FAULTS TO EARTH.

Sometimes there is evidence of a fault occurring intermittently. It may be that when the machine is stationary no fault can be detected but when it is running the fault makes itself evident. It may be that the fault occurs only under certain conditions of load or under certain magnetic conditions. These cases are often very difficult to deal with. Ingenuity must be exercised and a study made of the circumstances in each particular case to find out what is wrong. The guiding principle, of course, is to find out first the conditions under which the fault occurs and then to preserve the conditions while we are searching for the fault.

Sometimes the winding of a **rotating field magnet** will have a fault to earth when running which disappears when the machine is stopped. As the field magnet is provided with slip rings, communication can be made with the windings when running, so that it is possible to apply the bridge method, p. 10, whether the resistance of the fault is great or small. The magnetic method and drop in potential methods are not applicable to a field magnet while it is rotating. When a winding is not provided with slip rings and fault occurs only under running conditions, it may be necessary to put on slip rings in order to make a bridge test. A slip ring may sometimes be made by winding a band of copper wire over a press-spahn sleeve on the shaft.

Heating method.

A common way of finding in which field coil of a magnet a fault occurs is to pass current from one terminal through the winding to the fault and back through the frame of the machine. The machine is run under these conditions for a sufficient length of time to warm up the field coils through which current is flowing. It is then shut down as quickly as possible and the coils are felt with the hand.

Starting near the terminals by which the current was put into the winding, the coils are felt successively until a coil is reached which is much cooler than the preceding ones. The fault may then be either in that coil or in the coil immediately preceding it. Now if the machine is allowed to cool and current is then passed from the other terminal to the fault and the same procedure adopted, the coil in *which the fault* occurs will be indicated.

Intermittent earth due to magnetic effect.

Sometimes the coils on a stationary field magnet take up a slightly different position when magnetised than when unmagnetised. For instance, a series coil which when on load carries 2000 or 3000 amperes may under these conditions be attracted by the frame and moved so as to cause a fault in some part where the insulation is weak. When the machine is tested at no-load no fault is apparent and it is not until a certain load is reached that we become aware of it.

Where a circuit is completely insulated except for one fault, no current can flow through the fault and for that reason it is not in evidence. We therefore have sometimes the case of a machine which, though it has a fault to earth, ordinarily runs perfectly satisfactorily until another fault occurs at some other part of the circuit. If the second fault is intermittent in character and its position and the circumstances under which it occurs are unknown, we may have considerable difficulty in finding the source of the trouble. The best plan is to make a permanent earth on the circuit so as to bring into evidence any fault that may exist. If this fault is only brought about by some magnetic or heating condition we must make our test under that condition. For example, let us suppose that there is an intermittent fault to earth on a D.C. machine which only occurs when the machine is on load. The right procedure is to connect the negative terminal of the machine to earth through a resistance and an ammeter, then run the machine up to speed and increase the load until current passes through the ammeter. If no current passes, shut down and put the positive terminal of the machine to earth through a resistance and an ammeter. Run up again and increase the load; if now a reading is obtained upon the ammeter it shows that the fault we are looking for is on the negative side of the machine. The resistance can now be adjusted until the current amounts to, say 25% of full load current. If this current is leaking away from some part of the conductor on the frame, we may take the drop in potential in successive series coils, commutating coils and other connecting leads; and there is generally no difficulty in finding the point where the 25% of the current disappears. Sometimes an intermittent short only occurs when parts of the machine are heated to a certain temperature. Where this is so,

the test above described is carried out after the machine has been properly heated up.

If an **intermittent fault** to earth occurs on a **direct current armature**, current can only flow through it if there is another fault on the system. The current which then flows is an alternating current. This distinguishes a fault in the armature from a fault in the frame. A good plan is to earth a part of the external circuit through a resistance and allow a small current, say 5 amperes, to flow through the fault for about a second. This will generally have the effect of making the fault permanent and even if its resistance is high its position can be ascertained by the methods described on pages 18 to 21.

LOW INSULATION RESISTANCE.

Sometimes the winding of a machine, without showing any localised fault to earth, has a low insulation resistance owing to dampness. In these cases one must be very careful not to puncture the insulation by applying a high voltage to it. In the case of low voltage machines it is not even safe to apply the 500 volts of a megger until we are sure that the winding is dry enough to withstand it. Where the machine is very damp, the insulation resistance can be measured approximately by means of a 6-volt battery and a voltmeter. The connections are shown in Fig. 20. The negative terminal of the battery is connected to the frame which represents earth; the positive end of the battery is connected to the positive terminal of the voltmeter, while the negative terminal of the voltmeter can be connected to the winding of the machine to be tested, or alternatively connected direct to the negative terminal of the battery by means of a two-way key so that it then reads the voltage of the battery. Let V equal the voltage of the battery and v the reading of the voltmeter when connected to the winding. Then the insulation resistance, $R_I = \frac{R_V(V-v)}{v}$, where R_V is the resistance of the voltmeter.

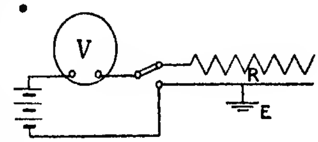


FIG. 20.

When a test of this kind shows that the insulation resistance is over 10,000 ohms, it will in general be safe to apply a megger, see p. 4, to make a more satisfactory measurement.

Drying out insulation.

By far the best method of drying out small machines is to heat them up in a vacuum oven. Where this method is not available

a common plan is to pass current through the windings until they become heated. The drawback to this procedure is that the cooling conditions in the various parts of the winding usually differ so widely that one part of the winding will become too hot before another part of the winding has been heated up enough to get rid of the moisture. This can be obviated to a certain extent by keeping the exposed parts of the winding free from draughts and even covering them up with wrappings, only allowing a little air to creep through to carry away the moisture. In any event it is extremely difficult to get the moisture out of coils that are insulated with a waterproof insulation. Where it can safely be done, as in the case of windings insulated with mica or asbestos, the raising of the winding above boiling point will get rid of the moisture very much more rapidly than a mere heating of the winding below that point, because we get a positive pressure of steam to force its way through the closed insulation. If the temperature is below boiling point in any part of the winding in the enclosed insulation, there is a tendency for moisture to move from the hotter parts and condense in the cooler parts. This concentration of moisture may lead to such excessive dampness of the cooler part that the danger of insulation breakdown is greater after the application of heat than it was before. Where the insulation consists of ordinary inflammable materials it is not in general safe to try to raise the temperature of the windings above boiling point. The danger is that those parts of the winding in which the cooling conditions are worse may reach a temperature at which the insulation is injured while other parts of the winding are still below boiling point.

The usual plan is to raise the temperature as high as is thought safe and leave it exposed to the air for several days, the insulation resistance being measured from time to time. It will generally be found that at first the insulation resistance falls. Fig. 21 shows how the insulation resistance of a D.C. armature varied with time while subjected to this drying out process. It will be seen that, after the first 6 hours' heating up, the insulation resistance had fallen to about 0·1 of its original value, and it was not until after three days of drying that it began to rise to a satisfactory figure. Even after the insulation resistance, as measured in the ordinary way, appears to have gone up during the drying-out process, it does not follow that the whole of the moisture has been got rid of. There may be certain parts of the winding, such as the ends, that project out into the air, which are not in contact with the frame and these may contain moisture without affecting the insulation resistance as measured. If this moisture is retained by a closed covering of waterproof insulation, it may still get back into the machine after the heating up process has been discontinued. The only way to

avoid this is to make sure that all parts of the winding have been brought to the highest safe temperature and that sufficient time has been allowed for the air to carry away the moisture driven

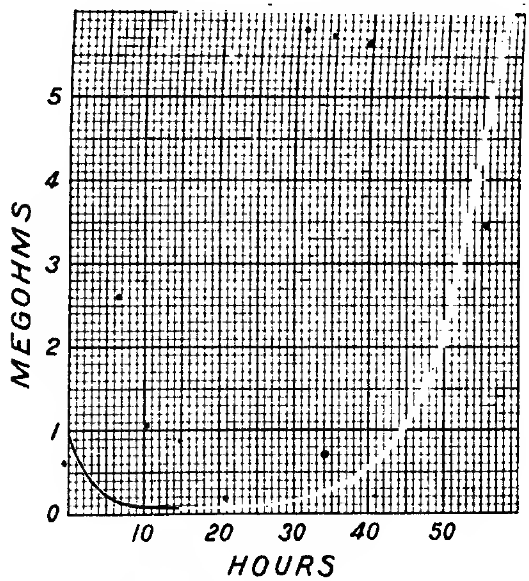


FIG. 21.—Curve showing change of insulation resistance during the drying-out period.

from the hottest parts which, in the first instance, collects in the cooler parts.

THE REPAIRING OF FAULTS IN INSULATION.

Armature coils.

The only satisfactory way of repairing an armature on which there has been an insulation breakdown is to replace the defective coil by a new armature coil properly insulated by the manufacturer. Sometimes, however, it is necessary to effect a temporary repair in order that a machine may be kept running while the new armature coil is being obtained. This should never be attempted unless it is known that a safe job can be made of the repair, because the breakdown of an armature coil when the armature is in operation may lead to such very bad burning of the iron that a great part of the armature has to be rebuilt. In cases of emergency, however, repairs may sometimes be effected, but they should be subjected to a severe puncture test before being put into service.

If the fault has occurred in an armature and there has been any arcing between the copper and the iron, it is extremely likely that the surface of the iron will be burnt and some of the laminations melted together. When this has occurred care must be taken that all the iron laminations are separated from one another before a new coil is put in the slot. The laminations can sometimes be separated by driving a strong steel blade between them at a point a few inches away from the burn and then hammering the blade forward towards the burn. It is a good plan to insert a thin piece of paper in each space between the laminations so as to keep them separated effectually.

A Turbo-generator stator will sometimes show weakness in the insulation near the end of the straight part of an armature coil at

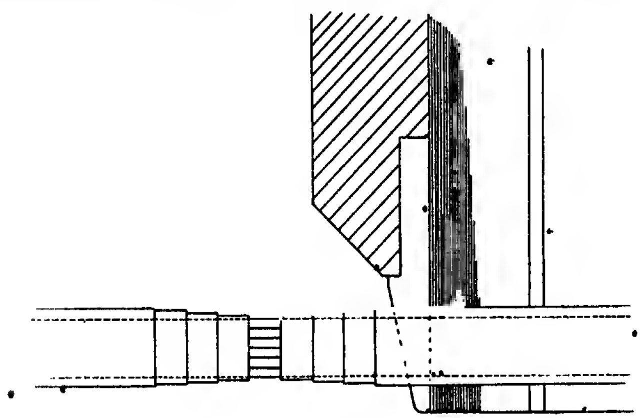


Fig. 22.

the point where it leaves the iron. In cases of this kind it has sometimes been possible to disconnect the end connectors and pull the armature coil further through the slot so as to expose the defective part of the insulation. The insulation has then been stripped off in layers, so as to leave the remaining insulation in step formation, as shown in Fig. 22. For a 6000 volt machine the length of stepped surface from the bare copper to the surface of the coil should not be less than 3". The insulation can then be built up with mica and empire cloth, care being taken to fill in each step so that the new insulation abuts neatly to the old. The empire cloth should be stretched fairly tightly so as to fit closely against the level surface of the steps and exclude air as far as possible. The second layer before the last should be painted with an air-drying varnish, the solvent of which should be naphtha rather than alcohol, and after the varnish is dry the last layer should be put on and the whole

re-varnished. The external surface should be taped with a smooth continuation of the old taping and should be finished without any excrescences that will put a drag upon the new insulation as it is being drawn into the slot. When completed the coil may be drawn back to its old position and the standard test applied between the conductors and frame. For high-voltage machines this test generally consists in the application for one minute of an alternating pressure of R.M.S. value equal to double the voltage of the machine. If the repair stands this test the end connectors may be re-connected and the machine put into service.

A fault in the armature end-connectors is generally more easily repaired because the end connectors are commonly insulated with empire tape or mica tape and the repair when carried out by a skilled winder can be made almost as good as on a new machine.

Direct current armature coils with voltages up to 700 volts.

These are ordinarily insulated with paper and mica, and as the normal voltage is not excessive there is no great difficulty in putting a completely new wrapping on the coil, which will make it almost as sound as a new one. It is not, however, possible to use an oven-dried varnish on a repair of this kind, and none of the air-drying varnishes are quite so satisfactory. It is better to wrap the whole of the straight part of the armature coil with a new wrapping, rather than attempt to patch one end. The taping of the individual conductors on the end windings may be treated with a coating of air-drying flexible varnish.

Field coils.

When a field coil has developed a fault to earth, an endeavour should be made to find the cause of the failure of the insulation. Sometimes the failure has been due to the too rapid breaking of the field current, which has caused a rise of pressure sufficiently great to puncture the insulation. Where this has occurred it is not merely sufficient to repair the coil. A suitable discharge resistance should be provided to prevent an undue rise of pressure. A metal sleeve or metal washer around the pole will also prevent an undue rise of pressure in a coil. If a field pole is provided with such a washer the resistance of whose circuit is r ohms, then the pressure rise in any one turn of the field coil can never be more than $A \times r$, where A is the total number of ampere-turns on the pole. If, for instance, the resistance of a metal washer around the pole is 0·0001 ohm, and the maximum number of ampere turns on the pole is 9000, then it is impossible that the voltage rise due to the sudden breaking of the field current shall be more than 0·9 of a volt per turn; so that a coil of 100 turns could not yield a rise in voltage of more than 90 volts,

and if there were 10 coils the total voltage rise in the field could not be more than 900 volts. Where solid metal poles are used, the solid metal of the pole acts in the same way as a metal washer, and prevents an undue rise of voltage when the current is suddenly broken.

Sometimes the breakdown may be found to be due to a cutting through of the insulation owing to excessive pressure in forcing on the coil. When this has occurred, measurements should be made of the coil dimensions and of the space available on the frame, and due provision must be made in arranging the parts so that excessive pressure does not come upon the insulation.

One instance of trouble of this kind is found in the bringing out of the terminals of wire-wound field coils. This is sometimes done by wrapping a copper strap around the wire of the coil, as shown in Fig. 23, and carrying the strap between the bottom layer and the layer second to the bottom so that the terminal may be brought out near the top of the coil. When this is done and the coil is tightly bolted down under the overhanging pole tips the various layers of wire in the coil yield slightly under the heavy pressure, but the copper strap, which is held between the layers so that it cannot buckle, does not yield and may cut through the insulation flanking the coil at the ends or injure the cotton covering of the wire. In a case of this kind the winding of the coil should be arranged so that the end of the inside wire is at the top instead of at the bottom. There would then not be so much tendency for the copper strap to buckle up. This case is mentioned merely as an illustration of the forethought that is necessary in designing the parts and insulation of field-coils which are subjected to heavy centrifugal forces or other compressive forces, and when a repair is carried out the same forethought must be bestowed if we are to avoid a second breakdown.

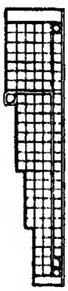


FIG. 23.

FAULTS IN INSULATION BETWEEN TURNS—SHORT CIRCUITS.

Short circuits in armature coils.

Where a short circuit occurs in an armature coil of a machine when in operation, it does not require much searching for, because it becomes very hot, and usually burns the insulation before it is observed; the "symptoms" then consist of the charred remains of the coil.

If, instead of one coil on the armature, we have a large fraction of the whole winding short-circuited, it may be that the short circuit current which flows through that portion of the winding is not sufficiently great to cause such very excessive heating. This may

easily occur in machines of poor regulation. In this case, however, the low voltage generated by the machine will lead us to look for a short circuit; and, measuring the resistance of the armature, we shall find that the total resistance is far below its normal value. If the machine is then run with the terminals open-circuited and the field-magnet excited to an amount just sufficient to pass a heavy current in the short-circuited portion, that portion will be indicated by its temperature rise. In the case of a 3-phase induction motor the resistance of whose winding is so low as to lead us to suspect that there are short-circuited coils, we can at once see in what phase the short-circuit is, because the resistance of that phase is lower than that of the others. If an inspection of the winding does not lead to a discovery of the position of the short-circuit, we may proceed to apply a low alternating voltage to the two terminals connecting the phases that are in good order. This voltage should then be increased until there is an indication of heating in the short-circuited coils. In this case the sound phases act as the primary of a transformer and the short-circuited coils act as a secondary.

In a test of this kind it is well to complete the magnetic circuit by placing inside the stator the unwound core of a rotor or a wound rotor with the winding open circuited. A squirrel-cage rotor will not do. Where the stator is wound for a high voltage it is sometimes more convenient to apply voltage to a wound rotor placed inside the stator rather than to the stator itself. The current should be switched off the machine before the coils are felt with the hand.

Shop tests for short-circuits. An apparatus commonly used for testing armatures during the course of manufacture is illustrated in Fig. 24. It consists of a laminated electro-magnet having poles of suitable shape to fit against the cylindrical surface of an armature, and its magnetising coil is supplied with an alternating current. A suspension on counter weights is provided so that it can conveniently be raised or lowered and accommodated to different armatures. When placed against the cylindrical face of an armature and switched on to the alternating current supply, the magnet supplies an alternating magnetic flux which threads through several of the armature coils. If the coil shown at AA' is short-circuited, a current

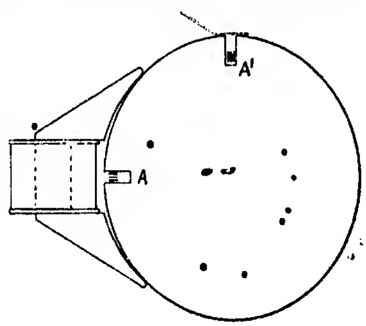


FIG. 24.

will flow in it, and the presence of this current can be ascertained by the attraction which is causes upon a thin strip of iron, dragged by the operator over the armature teeth at A'. All that is necessary, therefore, to test the armature is to subject the various bands of armature coils in succession to the influence of the alternating-current magnet, and feel for short-circuits by means of the strip of iron.

A similar apparatus having convex poles instead of concave poles, can be used for the internal cylindrical surface of stators. When such an apparatus is not available it is possible to test for short-circuits in a stator by putting a wound rotor, having the same number of poles and approximately the same diameter, into the stator and feeding the rotor with an alternating current. If the alternating current is slowly increased from zero and the stator coils are felt with the hand, it is possible to pick out any short-circuited coil by the fact that it warms up owing to the current generated by the alternating flux from the rotor core.

Telephone test for short circuits. A small search coil connected to a telephone can sometimes be used for telling the position of short circuits. Any D.C. armature with current fed in at two symmetrical points produces a magnetic field whose poles are at known positions with respect to the points where the current is led in and out (see page 12). If an alternating or interrupted current is fed in at two symmetrical points we can roughly judge the strength of the magnetic field at a point on the armature by means of a search coil attached to a telephone. A short-circuited coil produces a marked disturbance to the uniform distribution of the field and its position can be found in most cases with great ease because the current carried by the short-circuit coil is not only greater than the exciting current, but, being opposite in direction, it creates nodes on each side. The slot carrying the short-circuited coil has an intense field across the mouth, whereas the slots on each side will have a very weak field. When a three-phase winding is being tested by this method, the alternating current should be passed in at one phase and out by the other two phases. This will produce a perfectly symmetrical field distribution if there are no short circuits.

Testing for short circuits in individual coils before assembly. An apparatus which is useful for this purpose is illustrated in Fig. 25. In principle it is analogous to the Hughes induction balance. It consists of a three-legged laminated electro-magnet having a central magnetising coil MM, and two search coils SS', which are wound on the outer limbs so that normally the E.M.F.'s generated by the alternating flux in the limbs is opposed in the two coils. These coils are connected in series to a sensitive wattmeter. Alternating current is supplied to the exciting coil MM, and if proper adjustments are

made, there is no reading on the wattmeter until a short-circuited coil is brought into such a position that it embraces some of the flux from one of the outer limbs. The eddy-current in such a short-circuited coil in setting up an opposing back magneto-motive force disturbs the balance of the flux in the outer limbs, so that the E.M.F.'s in SS' are no longer balanced, and a reading is obtained on

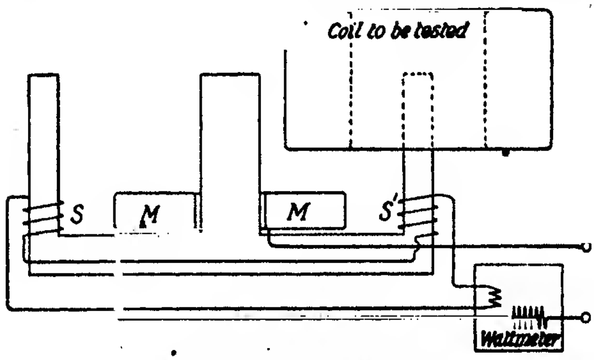


FIG. 25.—Induction balance for detecting the presence of a short-circuit in a coil.

the wattmeter. Sometimes a telephone is used instead of a wattmeter. This apparatus can be made very sensitive and will indicate faults of fairly high resistance in field-coils.

Drop in potential method. As this method is most generally used for finding short-circuits in field-coils, it is considered below under that heading; but it is of course also applicable to armature coils.

In dealing with a lap-wound D.C. armature by this method, the best plan is to leave the armature in its frame. Turn it round until a bar connected to a cross connector is directly under a brush and put little strips of copper under one brush in each brush arm, so that current can be led into and out of the armature by feeding current into the positive brushes and taking it out by the negative brushes. The strips of copper should be arranged so that each brush-holder is in contact with the bar connected to the positive or negative cross-connectors. In this way a more symmetrical current distribution is obtained than where the current is fed into the armature promiscuously. Then, while feeding a constant current through the armature, measure the drop in potential between each successive pairs of commutator bars by means of the instrument shown in Fig. 18. These drops should be very nearly equal until we come to a short circuit coil, when the drop will fall to a low value.

be expected from the current taken by it. This sometimes causes a want of symmetry in the field system of a D.C. machine, and may lead to results which are rather puzzling until the cause has been ascertained. Where the proper resistance of the coil is known the existence of a partial short-circuit is at once obvious, when the drop in potential across the coil is taken while a known current is passing. The best cure is to have the shunt coils dried out in a vacuum oven, and if the machine works in a damp situation the coils should be impregnated with petroleum residue after being so dried out.

OPEN CIRCUIT.

On a low-voltage armature wound with bars or copper strap an open circuit may occur through the unsweating of a connecting-thimble. The most useful appliance for finding an open circuit is the lighting-out set illustrated in Fig. 9. The terminals $T+$ and $T-$ are attached to the lighting circuit or other source of voltage, either continuous or alternating, from 100 to 500 volts. Lamps designed to withstand the pressure of the circuit are put in the two lamp-holders. For instance, on a 500 volt circuit two 250 volt lamps will be connected in series; whereas on a 110 volt circuit one of the 110 volt lamps will be put into one holder and the short-circuiting plug into the other holder. Now, if the two points $P+$ and $P-$ are connected by a conductor the lamps will light. The sharp points can be used to puncture insulation in positions on an armature where no damage is done by such puncturing or where the damage can be easily repaired. The lighting up of the lamps serves as a very convenient means of testing the continuity of the circuit.

Low voltage polyphase armatures.

Distinction should be made between star-connected armatures and mesh-connected armatures.

Star-connected armatures. If we take the case of a 3-phase star-connected armature on which there is a break in phase A, there will of course be no path either from A to B or from A to C, but there will be a path from B to C. If we employ the lighting-out set, we can ascertain at once that the open-circuit is in A. Now, puncture the insulation at the end of one of the bars near the middle of phase A and test for continuity of circuit between that point and the terminal of phase A. If no circuit is shown, test the continuity of the circuit from a point a quarter of the way along A to the terminal, and so on until the position of the open circuit is definitely ascertained.

Mesh-connected armatures. In a mesh-connected winding whose meshes are A, B and C, and whose terminals are P, Q and R, as

indicated in Fig. 27, in whatever phase the open circuit occurs, we can always pass current between any two of the terminals. If there is an open circuit in phase A, the resistance between P and R is twice as great as the resistance between P and Q or Q and R. When it is found that the open circuit is in A, we should disconnect the ends of A from P and R, and make a test with the lighting-out set from the middle of A to one of its ends, and so on as on the star-connected machine.

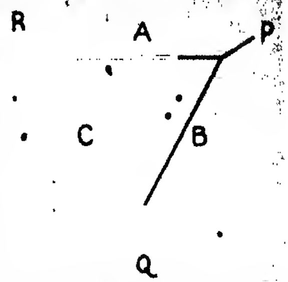


FIG. 27.—Mesh connected armature with open circuit in phase A.

Two-phase windings, single-phase windings or field-windings can be tested out in the same way.

High voltage armatures.

Where we have to deal with a high voltage armature with a completely enclosed insulation, it is not desirable to make any more punctures in the insulation than are absolutely necessary. It is generally possible to separate the phases and test each phase singly. Treating each phase as a single-phase, a measurement of the capacity of each section of the winding between its terminal and the open circuit will sometimes give a fairly good indication of the position of the break, if the break is complete. The method that we use to measure the capacity of the winding will depend upon the apparatus that is available. If a fairly sensitive ballistic galvanometer is available, one of the simplest methods of measuring the capacity is that illustrated in Fig. 28. One terminal of a 6-volt battery

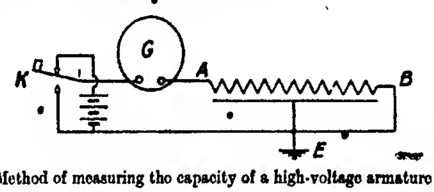


FIG. 28.—Method of measuring the capacity of a high-voltage armature winding.

is connected to the frame of the machine, the other terminal being carried to the upper terminal of a two-way spring key, K, which connects the upper terminal through the ballistic galvanometer to one terminal A of the winding, the terminal B being earthed. This raises the potential of the A section of the winding 6 volts above the frame. After the ballistic galvanometer has come to rest the key is quickly depressed so as to discharge the winding through the galvanometer. Let the deflection obtained be D_A. The galvanometer is then connected to the terminal B (A being earthed), and

another deflection D_B is obtained; then the number of coils in the A section of the winding is to the number of coils in the B section of the winding approximately as D_A is to D_B. The validity of this statement is of course dependent upon the assumption that the thickness and character of the insulation of all the coils is the same.

Where no means of measuring the capacity of the winding is available we may make a measurement of its insulation resistance. The variation in the insulation resistance of any section of the winding, however, is a matter much more dependent upon accidental circumstances than the capacity is so dependent. In cases, however, where the break in the circuit is complete, the insulation resistance measured from either end of the winding gives us some indication of the probable position of the break; the higher the insulation resistance of the section that is measured, the shorter that section is likely to be. Having obtained a fair indication as to the approximate position of the open circuit we may now proceed with the lighting-out set to find its exact position.

Open circuits on commutating machines.

Lap-wound D.C. armatures with a great number of cross-connectors have in them so many paths in parallel that we must proceed on a definite plan, if we are to find an open circuit with certainty. The best plan is to choose two cross-connecting rings, which will be of opposite polarity when the machine is running; that is to say, two connecting rings which are exactly a pole pitch apart. Find two commutator bars, each connected to one of these rings, and pass a current of say 10 amperes in at one bar through the winding to the other bar. If the armature is mounted in its field-frame, the method of feeding in current described on page 33 may be adopted. Connect the voltmeter points, Fig. 9, to an armature detector (Fig. 18), or a milli-voltmeter suitably shunted to withstand the maximum voltage on the commutator, and put one of the points on the bar where the current enters and the other point on the next consecutive bar. Measure the voltage drop between the bars and then proceed to measure the volts between each consecutive pair of bars. If there is an open-circuit in any section of the winding lying between two points from which taps go to cross-connectors, it will be found that there is no voltage drop between the bars belonging to that section, until we come to the pair of bars between which the break occurs. The drop then is very decided. After we have passed this pair of bars there is no drop again until we come to the end of the section. This statement is only true if the current is passed into and out of cross-connected points that are exactly a pole-pitch apart. If we merely pass current in at one bar of a commutator, and

out at any other bar promiscuously, it may be possible to find several regions on the commutator where no voltage exists between bars although there may be no open circuit on the winding at all.

Two-circuit windings.

As these windings have no cross-connectors, we may choose any two points on the commutator (preferably two points a pole-pitch apart) at which to lead in and take out the current. If there is an open circuit, there will be only one path through the winding instead of two paths. The current in the enclosed path will cause a drop between pairs of commutator bars belonging to that part of the winding. There will be no drop between commutator bars in the open-circuited part of the winding except at one point near the break. The procedure, therefore, is to feed current in and take current out at two points a pole-pitch apart and find the region on the commutator on which all the bars are at the same potential. The feeding-in point is now moved step by step towards the taking-out point until a bar is reached which is connected to a conductor just beyond the break in the circuit. There will now be a difference of potential between bars in what was before a blank region. The position of the break in the circuit is thus indicated.

Doubly and trebly re-entrant multiplex windings.

These may be dealt with in exactly the same way as lap-wound armatures, except that on a duplex armature the voltmeter points should always be kept two bars apart, that is to say, they should be placed on bars 1 and 3 instead of bars 1 and 2. On a triplex winding the voltmeter points should be kept three bars apart. The current should, of course, be led into and out of the particular section of the winding under examination.

Arnold singly re-entrant multiplex winding.

If a winding of this kind* has $2a$ circuits in parallel, we should short-circuit a bars at as many points as the machine has poles, the short-circuited points being evenly spaced around the commutator. This is conveniently done by putting a wires under brushes at each brush-holder, so as to make the brushes connect definitely with a bars. We can then pass current through the $2a$ circuits in parallel. We can now take the voltage drop between pairs of bars which are a bars apart. Thus where $a=3$, we should place the voltmeter points on bars 1 and 4, 2 and 5, and so on, proceeding step by step around the commutator. A break in the circuit will be indicated by there being no drop in potential between the pairs of bars between the feeding-in point and the break and a big drop of potential at bars between which the break occurs.

* See *Specification and Design of Dynamo Electric Machinery*, page 511.

Partial open circuit.

Sometimes an armature of a dynamo, while not actually open-circuited, has a high resistance introduced at one or more points owing to defective joints. The general procedure is the same as for an open-circuit, but the indications are not quite so positive. There will be some drop in potential between all bars in the defective section. The partial open-circuit is indicated by the greatness of the drop at the bars between which the defect occurs. Another procedure is to measure the resistance of two halves of the winding that ought to be exactly similar, so that the presence of the partial open circuit in one of the halves can be detected. On dividing this half up again in two portions and testing again and so on, the position of the defect in the winding can be ultimately traced out.

High resistance in parallel branches.

Sometimes two circuits are intended to operate in parallel, as for instance, the series coils or commutating coils of D.C. machines intended for very large currents. A defective joint may occur which makes the resistance of one circuit appreciably different from that of the other so that the current, instead of dividing equally, divides inversely as the resistance and leads to defective operation. When such a state of affairs is suspected, one of the best ways of finding out whether the current is divided equally is to measure the drop of potential in a coil in each of the branches while the machine is in operation. In doing this, care must be taken that the voltmeter points are put directly in contact with the copper of the coil under test, so that in the circuit between the two points there is no joint. If the two coils are exactly similar in every way and are at the same temperature, the drop in the coil will be proportional to the current passing through it, and thus the symmetry of the two circuits can be checked. The defective joint can be found by taking the drop across each of the joints and comparing them.

Open circuit in field windings. The most usual method of finding the position of such a fault is to connect one end of the winding to the negative supply main and connect the $+T$ of the "lighting-out" set shown in Fig. 9 to the positive main, and then explore with the point $+P$. The fault lies between a point where the lamps will light and a point where the lamps will not light.

CHAPTER II.

OVER-HEATING.

MEASUREMENT OF TEMPERATURE.

The Thermometer.

THE thermometer is used as a means of measuring the temperature of various parts of a dynamo on account of its portability and general convenience in use. It cannot be regarded as a very satisfactory means of arriving at the true temperature of the part in question.

Where we are dealing with a stationary part such as a field coil of a D.C. generator, it is sometimes possible to fit the thermometer into a crevice in the coil and leave it there during the whole of the heat run, in which case it may give a very fair indication of the temperature rise of the parts immediately surrounding it. Where this is done some judgment must be exercised as to the amount of padding to put around the thermometer to protect it from air currents. If no padding is put around it the draught of air in the vicinity may prevent it from attaining the temperature of the adjacent coil. On the other hand if too large a pad is used it will prevent the proper cooling of the coil so that too high a temperature will be attained. The best plan is to see that the bulb of the thermometer is in as close contact as possible with the surface whose temperature is to be measured and a pad of cotton wool not exceeding two inches by two inches and one inch thick should be closely pressed over the bulb so as to exclude it from draughts of air. If it is possible to find any part where the two sides of the thermometer can be brought into contact with the surface, so much the better (see Fig. 29).

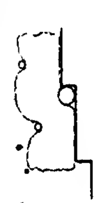


FIG. 29.

Where the temperature of the revolving part of a machine has to be taken it is usual to put the thermometer in position after the machine has come to rest. As a rule, the surfaces of revolving parts of a dynamo are fairly cool while in motion and do not reach their maximum temperature until a few minutes after the machine has come to rest. For instance, where the cotton-covered wire-wound field coils of a revolving-field generator are felt by hand immediately

the field has come to rest, it will generally be found that they are not as warm as when felt a minute or two afterwards. This is because, *notwithstanding the high temperature of the copper in the interior of the coil, the heat conductivity between the layers of wire does not* permit the surface of the coil to reach a very high temperature when it is subjected to high velocity air currents. In addition to the interval of time which is necessary for the heat in the inside of the coil to reach the surface, a further interval of time is required for the heat to pass through the glass bulb of the thermometer and warm up the mercury. The time taken for the heat to pass into the bulb of the thermometer will depend upon the heat conductivity of the material in contact with the glass bulb. Where a coil is wrapped with several layers of tape which contain air spaces in between, the heat conductivity may be so poor that a fairly large thermometer bulb may take 10 or 15 minutes to receive from the surface the heat that is necessary to make it give approximately the correct reading. In addition to the heat required to warm up the bulb there is often an even larger quantity of heat required to warm up the cold pad of cotton wool or waste put over the thermometer to "keep it warm." During these 10 or 15 minutes the heat from the inside of the coil is being conducted to the frame and being carried away by convection; so the temperature recorded by the thermometer may be not more than half of the temperature normally reached by the surface of the coil. Anyone who has had experience of temperatures taken on a large number of machines of standard construction knows how very unreliable the temperature readings as ordinarily taken are. For exactly similar machines run under exactly similar conditions, the temperatures recorded differ over very wide limits depending upon the manner in which the thermometers are placed and the care taken to ensure that the thermometer reaches as nearly as possible the temperature that would be reached by the part under normal conditions.

When a temperature guarantee is based upon a temperature measurement by thermometer, it is of course assumed that the contractor is to have the advantage of the poor conductivity that ordinarily exists between the thermometer and the part to be measured. How far the unscientific methods ordinarily in use for measuring the temperature by a thermometer may be legitimately replaced on an official test by more accurate methods which might lead to higher readings is a matter open to dispute.

Maximum temperature reached in the long run.

Very large electrical machines take a considerable time to reach their maximum temperature. By making observations during a run of a few hours it is sometimes possible to determine with fair

accuracy the maximum temperature that would be reached if the run were indefinitely continued. This matter is made rather more difficult on account of the very irregular law of temperature rise of a dynamo during the first stages of heating. If we had a solid block of copper in which heat was being produced at a uniform rate per cubic centimetre and if the cooling conditions were such that the number of watts radiated was proportional to the temperature rise, the law of temperature rise with time would be comparatively simple. In an ordinary electric machine, however, the heat is produced in some parts and conducted to others having a different heat capacity so that the law of temperature rise in the early stages is very complex and differs for different parts of the machine.

Let us take the simple case first. In what follows we shall use the following units. The constant losses measured in kilowatts are denoted by W; the number of kilowatts dissipated per degree centigrade rise by K; and the heat capacity of the machine measured in kilowatt-hours per degree centigrade rise we will denote by H. The hour is taken as a unit of time.

Then:

$$H\frac{dT}{dt}+KT=W. \quad \text{.................................(1)}$$

The solution of this is

$$T=\frac{W}{K}\left(1-\epsilon^{-\frac{K}{H}t}\right) \quad \text{.................................(2)}$$

where T is the temperature rise in degrees centigrade and t is the time in hours measured from the commencement of the load run. If we take the values $W=175$ k.w., $K=5$ k.w. per degree rise and the heat capacity of the machine $H=6{\cdot}25$ kilowatt-hours per degree rise, we get the following law of the change of temperature rise with time: $T=35(1-\epsilon^{-0{\cdot}8t})$. In Fig. 30 we have plotted temperature against time. The curve is the same shape as the curve of rise of current in an electric circuit containing inductance and resistance to which a constant voltage is applied. The maximum temperature which will be reached in an indefinitely long run is $175\div5=35°$ C. If we draw a tangent OA to the curve through the origin we find that it cuts the 35° line at A at the time 1·25 hours. If we take t at 1·25 hours in the expression $(1-\epsilon^{-0{\cdot}8t})$ the index of the powers of ϵ becomes -1 and the $\epsilon^{-1}={\cdot}3678$ so that the value of $(1-\epsilon^{-0{\cdot}8t})$ is then equal to 0·6322. A well-known characteristic of these curves is that at the point where the tangent to the origin cuts the horizontal line through the maximum the value of the ordinate of the curve is 0·6322 of the maximum.

In an actual machine during the first stages of heating up the time-temperature curve does not follow the same law as in the simple case considered above. The heat is produced in some parts of small

heat capacity surrounded by insulation, so that the temperature rise in these parts rises fairly rapidly. It is then conducted to other parts having often a larger heat capacity, so that the temperature rise there is not so rapid. The temperature rise in each part of the machine follows a law of its own; but if we confine our attention to one part, say the stator iron behind the slots, we shall find that after a one or two hours' run the temperature is following very closely

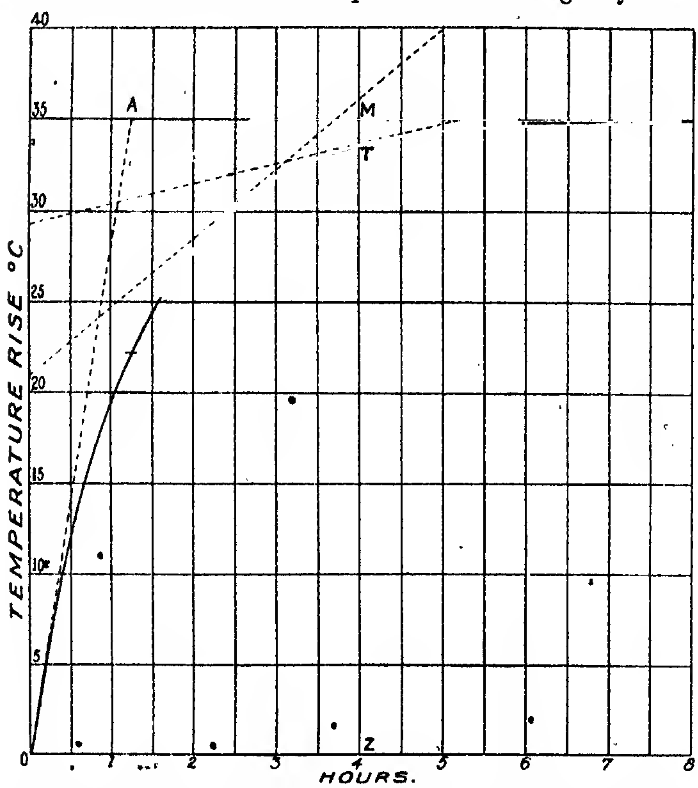


FIG. 30.—Time-temperature curve showing how the final temperature can be predicted.

the law given in the expression (2) p. 43. This is because the part in question has a definite heat capacity, and after the preliminary stages of warming up it receives heat at a constant rate, and gives off heat at a rate proportional to its temperature. Thus we can say that though in the first stages the curve in Fig. 30 is not applicable to the temperature rise of an electrical machine, it is applicable in the final stages; and if we can find the ratio of K to H the line to which the curve becomes asymptotic can be obtained without running the machine for very many hours.

If we run the machine for several hours until the time temperature curve approaches the horizontal, having only a very gentle slope upwards, we may guess the position of the horizontal line with sufficient accuracy for practical purposes. If it is desired to calculate its position with greater accuracy, the following method may be employed:

Suppose that a machine is run for 5 hours, and the temperature of a certain part, say the stator iron, is found during the last three hours to follow the law illustrated in Fig. 30. Select two points on the curve say at $2\frac{1}{2}$ hours and at 4 hours, and draw tangents to the curve as shown by the dotted lines. The slope of these tangents can then be expressed by taking the ratio of an ordinate of the tangent expressed in degrees centigrade to the abscissa expressed in hours. For instance, the slope of the tangent to the curve at the point $2\frac{1}{2}$ is $\frac{18 \cdot 95}{5} = 3 \cdot 79$, and the slope of the tangent to the curve at the point 4 hours is $\frac{5 \cdot 85}{5 \cdot 17} = 1 \cdot 138$. Now take the napierian logarithms of these ratios. These are 1·33 and 0·13 respectively. The difference between these is 1·2, and the difference between $2\frac{1}{2}$ hours and 4 hours is $1\frac{1}{2}$ hours. Now $\frac{1 \cdot 2}{1 \cdot 5} = 0 \cdot 8$, and this is equal to $\frac{K}{H}$, the coefficient of t in equation (2).* Knowing $\frac{K}{H}$ we can calculate by what fraction of the maximum temperature rise any point on the curve is below the maximum temperature rise. For instance, in Fig. 30, the ratio of MT to MZ is equal to $\epsilon^{-\frac{H}{K}t}$. If we take $t = 4$ hours and $\frac{K}{H} = 0 \cdot 8$, then the ratio of MT to MZ is equal to $\epsilon^{-0 \cdot 8 \times 4} = 0 \cdot 04$, that is to say, that after 4 hours the temperature has risen to a point within 4 per cent. of the maximum temperature. By employing this method we may in the course of a few hours' run ascertain the temperature to which the machine would rise if run for an indefinitely long time.

* The proof of this is

$$T = \frac{W}{K}\left(1 - \epsilon^{-\frac{K}{H}t}\right).$$

$$\frac{dT}{dt} = \frac{W}{H}\epsilon^{-\frac{K}{H}t}.$$

$$\log_\epsilon \frac{dT}{dt} = \log \frac{W}{H} - \frac{K}{H}t.$$

Now take the slopes $\frac{dT}{dt}$ at two points t_1 and t_2, and find the napierian logarithms of the values found. Then

$$\left(\log_\epsilon \frac{dT}{dt}\right)_1 - \left(\log_\epsilon \frac{dT}{dt}\right)_2 = \frac{K}{H}(t_2 - t_1).$$

$$\frac{K}{H} = \frac{\left(\log_\epsilon \frac{dT}{dt}\right)_1 - \left(\log_\epsilon \frac{dT}{dt}\right)_2}{t_2 - t_1}.$$

Another method of shortening the run is to heat up the machine quickly by means of extra losses. The machine may be run on overload until the guaranteed temperature is reached. It is then put on normal load, and careful observations are made to ascertain whether the temperature rises or falls. If it falls we know that the part in question will meet the guarantee. If it rises, the temperature should be taken still higher by means of a short overload run, and tests made again at normal load, and so on until a steady temperature is reached.

By thermo-couple.

Fig. 31 gives a diagram of the connections of three thermo-couples *A*, *B* and *C*, arranged so that either one can be connected at will in circuit with a micro-amperemeter *M*. The return path is

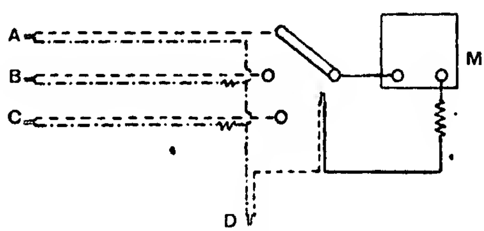


Fig. 31.

through a fourth thermo-couple, *D*, which must be maintained at a known temperature. If *D* is at the temperature of the air, taken as a standard, the readings obtained in *M* are proportional to the temperature rise above the air temperature. If the couples have not been calibrated before with the lengths of wire provided they should be calibrated after the connections have been made and little resistances inserted in series with each one to make the calibration of the instrument the same for all couples. The iron wire in Fig. 31 is shown with simple dotted lines, and the eureka with chain-dotted lines. The remainder of the circuit is of copper. It is important that the point of the circuit where we pass from eureka to copper shall always be at the same temperature as the point where we pass from copper to iron. For this reason it is well that these points should be kept near to one another. It is well to immerse junction *D* in an oil bath together with a thermometer, so that its temperature may be known.

The calibration curve of an iron-eureka couple is very nearly a straight line. The deviation from the straight line is so small for temperatures between 0° and 150° C. that if we insert resistance

in circuit with a micro-amperemeter until 100° C. difference of temperature gives a reading of 100, the instrument will read the difference of temperature between the hot and cold junctions with sufficient accuracy for practical purposes. The corrections to be applied to give the temperature with greater accuracy can be taken from a curve worked out by Dr. Narker and given by Mr. Rayner in the *Jour. Inst. Electrical Engineers*, vol. 34, p. 722 (1905). The error at 50° C. is about 0·3° C.

A thermo-couple may be used for measuring the temperature of parts of a dynamo, by being either laid in the part in question during construction, the wires being brought out to a convenient point or applied at the surface of the part in question after the machine has come to rest. The thermo-couple most commonly used for measuring the temperatures of electrical machinery is the iron-eureka junction. The E.M.F. in the circuit may be conveniently read by means of a delicate milli-voltmeter (see Fig. 1). Where very exact measurements of temperature are required it is well to keep the cold junction at zero temperature by surrounding it in melting ice, but for many purposes it is sufficient to keep the cold junction at the temperature of the surrounding atmosphere and take the difference of temperature between the junctions as equal to the milli-volts multiplied by a constant. This gives at once the temperature rise of the part in question, with sufficient accuracy for practical purposes. In placing a thermo-junction in position for the purpose of measuring the temperature it is well, where possible, to have the whole junction circuit insulated so as to be sure that there is no E.M.F. affecting the galvanometer other than that generated by the temperature difference. In some cases, however, it is inconvenient to completely insulate both wires of the thermo-junction; and if proper precautions are taken to eliminate all causes of E.M.F. other than the one sought to be measured, this course may be satisfactory. In insulating a thermo-couple we must be careful not to put too great a heat-insulator between the junction and the part whose temperature is to be measured. Only a very small part of the heat communicated to the junction is converted into electrical energy, so that the danger of the temperature of the junction being affected by this disappearance of heat is not of consequence in practical cases; but the wires of the junction have some thermal conductivity and under certain conditions may abstract some of the heat. Where the junction is intended to measure the temperature of a "hot spot" in a comparatively confined area, there is a danger of the junction assuming the mean temperature of the wires which may pass near a cool point not very far away from the hottest point. One of the best ways of ensuring that the junction is actually at the temperature of the material immediately surrounding

it is to use a rather thin wire, say not more than 28 gauge. After a junction has been made by sweating the iron and eureka together *for a length of one centimetre, the junction should be flattened out with a hammer so as to make a little spatula about 0·03 cm. thick. This can then be insulated by flanking it* on both sides with small pieces of treated paper 0·02 cms. thick, stuck on with shellac varnish. The iron and eureka wires may be double cotton covered, and the whole covered with a cotton stocking drawn tightly over the wires, dipped in sterling varnish, and dried in an oven. After a junction of this kind has been put in position, care must be taken that no undue pressure is to be put upon the wires so as to cut through the insulation between them. It is also important to see that the wires are everywhere supported mechanically so that they cannot vibrate; otherwise it may be found, after running the machine some time, that the circuit is broken. Where a large number of junctions are used to take the temperatures of the large number of points in a machine, it is well to employ a multi-contact switch for switching the various junctions in succession to the milli-voltmeter. All contacts of this switch should be made of the same metal, say brass, of the same quality. Care should be taken that all points of contact have a very low resistance and are maintained at a uniform temperature throughout, otherwise thermo-electromotive forces may be set up at these contacts which will affect the readings. The lengths of all the circuits should be adjusted until the calibration curves of all junctions are the same.

Where a thermo-electric junction is employed instead of a thermometer for taking the temperature of a surface after a dynamo has come to rest, it may be conveniently constructed of No. 24 iron and eureka wire, sweated together and hammered out into a spatula 1 cm. long and 0·3 cm. wide. As the other parts of the thermo-electric circuit can in general be kept completely insulated, this thermo-couple may be left uninsulated and brought directly into contact with the part whose temperature is to be measured. As its heat capacity is extremely small it will give an almost instantaneous reading of the temperature. It should be covered by a pad of cotton wool or felt whose dimensions may be $1'' \times 1'' \times \frac{1}{2}''$ thick. This pad serves to press the junction closely in contact with the surface of the machine and keep off cooling air currents. It would not be fair to regard the temperatures recorded by such an instrument as "temperatures taken by thermometer"; but in many investigations into the cause of undue temperature rise, where it is desired to take the actual temperature of various parts rapidly and accurately, this thermo-junction will be found extremely useful. For instance, a question may sometimes arise as to whether an undue rise of temperature found on a field-magnet is due to excessive

heating of the pole-faces, the heat being conducted along the pol
so as to interfere with the cooling of the field-coils, or whether th
high temperature of the pole-face is caused by the high temperature of the field-coils. This question can be most easily settled by finding the distribution of temperature in the end plate of the field-pole immediately after a temperature run. To make this measurement, two exactly similar thermo-junctions should be prepared. The machine is rapidly slowed down after a temperature run; one junction, A, is placed on the end plate of the pole close to the air-gap, and the other, B, against the end plate an inch or two away from the air-gap. If the temperature of A is higher than B the heat is being conducted from a pole face inwards. If the temperature of B is higher than A, the heat is being conducted from the pole-body to the pole-face. The same method can be used for settling the question whether excessive temperatures experienced in the end connectors of armature windings are due to the losses in the end connections or due to losses in the iron or buried copper.

Another type of thermometer which is very accurate and convenient for insertion in various parts of a dynamo is the resistance thermometer. It consists of a small coil of wire whose resistance is changed with change of temperature. The Cambridge and Paul Scientific Instrument Co. supply a very convenient form together with a bridge for measuring the resistance, the whole being calibrated to read direct in degrees Centigrade.

By resistance measurement.

It is not uncommon for a machine to be sold under a temperature guarantee relating to the field coils, the temperature to be measured by increase of resistance. This method has the advantage of giving the mean temperature rise of the whole field copper, but does not in general show us whether any parts of the winding are much hotter than the others. The coefficient of increase of resistance of copper with temperature depends upon the temperature at which we are working. It also depends somewhat on the purity of the copper, very small percentages of impurity affecting the shape of the temperature-resistance curve. For the almost pure copper employed in electrical machinery, it is usual to assume that the temperature-resistance curve is a straight line sloping upwards from $-234{\cdot}5°$ C. The following formula then gives the temperature rise in degrees centigrade:

$$t_r = t_2 - t_1 = (234{\cdot}5 + t_1)\left(\frac{R_2}{R_1} - 1\right),$$

where R_1 is the initial resistance at temperature t_1, and R_2 is the resistance at the higher temperature t_2.

Any engineer may make for himself a simple scale on his slide

rule that will give him at once the change that has occurred in the temperature of a copper circuit, when a change in the resistance is known. A reproduction of the scale is given in Fig. 32. It can be made in a few minutes by observing the following instructions: Most slide rules are provided with a tangent scale on the back of the sliding stick. This is graduated from about 5·7° at one end to 45° at the other. The part of the scale between 8° and 12° is shown in Fig. 32. With the point of a pen-knife, lengthen the graduations at the points 8°, 8° 20′, 8° 40′, and so on, and mark these points 0, 10, 20, 30, etc., respectively as shown in the figure. Reverse the tangent scale so that it comes next to scale *D* on the slide rule. Opposite the figure on scale *D* which represents the resistance at the lower temperature, put the number on the new scale representing that temperature; then on scale *D* the resistances at other temperatures are opposite the respective temperatures on the new scale. For instance, if we have a resistance of 42 ohms at 10°, put the number 10 on the new scale opposite 42 as shown in Fig. 32, then

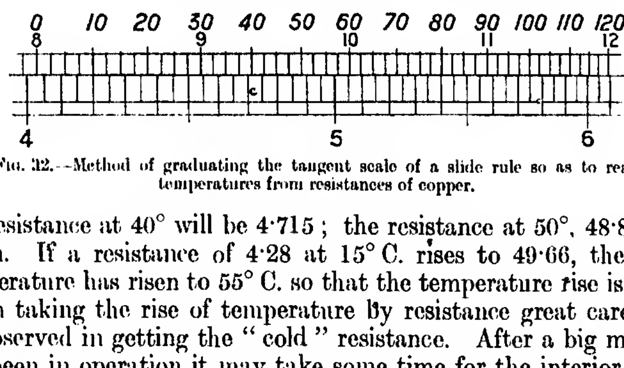


FIG. 32.—Method of graduating the tangent scale of a slide rule so as to read temperatures from resistances of copper.

the resistance at 40° will be 4·715; the resistance at 50°, 48·85, and so on. If a resistance of 4·28 at 15° C. rises to 49·66, the mean temperature has risen to 55° C. so that the temperature rise is 40° C.

In taking the rise of temperature by resistance great care must be observed in getting the "cold" resistance. After a big machine has been in operation it may take some time for the interior of the field-windings to reach the outside temperature and although the field may feel cold the temperature of the internal windings may be a good deal higher than the outside. For this reason it is well to have at hand the "cold" resistance as measured before the machine was run. The actual temperature at which the "cold" resistance is taken should always be recorded.

Measurement of the temperature of part of the winding by resistance.

It is sometimes possible to ascertain the temperature rise of different parts of a winding, say of the buried copper and the end connectors by measuring the change in potential drop in these parts when they are cold and when they have been heated up on load. For this purpose the steel voltmeter points illustrated in Fig. 9 are useful. When the machine is perfectly cold, having been standing,

for two or three days unused, pass a current so small as not appreciably to alter the temperature of the windings during this test. Prick through the insulation at the ends of a buried conductor and measure the drop in potential due to the resistance of that conductor. Do the same for an end connector. It is best to make a number of tests on a number of different conductors marking the points with chalk where the insulation has been punctured with the steel points. Now heat up the machine by running it on load, and immediately on shutting down take the potential drops again at exactly the same points as before. If there is any marked difference in temperature between the buried copper and the end connectors this will be shown by the resistance measurements. As it is possible by means of a delicate milli-voltmeter to get quite reliable readings of the potential drop in a few inches of conductor this method is sometimes useful for indicating the position of "hot spots."

Over-heating of a dynamo may be due to excessive losses or it may be due to defective heat dissipation.

Most of the cases of excessive losses in the iron and copper are dealt with in the next Chapter because we are most chiefly concerned with them under the heading of efficiency. Apart from excessive iron and copper losses occurring under normal load conditions, excessive losses may occur owing to a mistake in the operation of the machine. A generator may be running at a voltage considerably above its normal owing to a mistake in the voltmeter or in the ratio of its transformer, and the iron loss and field loss occurring under these circumstances may give rise to excessive temperature. During a temperature run a comparison should always be made of all the available data such as voltage, speed, field-current, etc., with the data taken on the original test of the machine (or with designers' data, if there is no previous test) to see that they check. Any want of correspondence in the data puts the tester on his guard against errors that he may make, however careful he may be. Again, a mistake may be made in the measurement of the current so that the load on the machine is much greater than is intended. This can easily arise in the case of alternating current generators, through misconnection or mistake in the ratio of transformation of the series transformers. Too much care cannot be taken with every link of the chain of the argument by which we arrive at our statement as to the actual load-current flowing and in the case of polyphase machinery we must of course see that all phases are balanced. (See p. 162.)

Defects in heat dissipation.

The heat generated in the copper and iron of an electric generator has a perfectly definite path along which it flows from the place

of its origin to the place where it is dissipated to the outer atmosphere. Heat can travel in three different ways—by conduction; by convection; and by radiation. The first two are by far the most important in the cooling of electrical machinery. The heat generally begins its journey on a conduction path, being generated in the body of a copper wire or in the iron core. Both copper and iron and in fact all metals conduct heat so well that we seldom have to complain that the undue rise of temperature is caused by the failure of the metals to do their duty in this respect. It is usually the bad heat-conducting substances such as solid insulation or air that act as the obstruction in the heat path. A convenient method of expressing the heat conducting qualities of a material is to give the heat flow, expressed in watts, which will flow between opposite sides of a centimetre cube when the difference in temperature between these sides is 1° C. Expressed in these units and also in inch units the following table gives the heat conductivity of several materials used in dynamo construction:

TABLE I.

HEAT CONDUCTIVITY OF VARIOUS MATERIALS USED IN DYNAMOS.

Material.	Thermal Conductivity.	
	Per sq. cm. per °C. of difference of temperature per cm	Per sq. in. per °C. of difference of temperature per inch.
	In watts.	*In watts*
Copper	3·8	9·6
Steel punchings along laminations	0·63	1·6
Steel punchings across laminations (10 per cent. paper insulation)	0·0118	0·03
Cast iron	0·125 to 0·25	0·32 to 0·64
Brass	0·84	2·14
Press-spahn	0·0017	0·0042
Varnished cloth (empire cloth) tightly wrapped	0·0025	0·0063
Empire cloth, mica and tape containing some air-spaces	0·0015	0·0038
Built up mica	0·001 to 0·0012	0·0026 to 0·0031
Linen tape, treated	0·0014	0·0037
Stationary air	0·0002	0·0005

When the heat arrives at any surface bounded by air it is necessary if it is to pass any further to proceed through the air. The heat conductivity of stationary air is exceedingly poor as will be seen

from the above table and we can never get satisfactory dissipation of heat from a metal surface, if it is bounded by stationary air. *If the air is in motion the heat is carried by convection; the more rapidly the air can be changed the more rapidly we can get rid of the heat.* In order that a solid surface may give up its heat rapidly in this way it is desirable that the air in very close proximity to the surface should be moving rapidly. This is a condition rather difficult to maintain. Though we may have a very rapid current of air a few centimetres from the surface, the air in contact with the surface may move only slowly.

The following data are useful in calculating the amount of air necessary to get rid of the heat generated in any particular electric machine:

$$\text{Cubic metres of air per sec.} = \frac{\text{watts lost}}{\text{temp. rise of air} \times 1150}.$$

This assumes a barometric pressure of 760 mm. of mercury, and a mean temperature of 35° C. To get the volume at any other pressure, p in mm., and temperature, T in °C, multiply by

$$\frac{273+T}{273} \times \frac{760}{p}.$$

One generally allows 50 per cent. more than this in cases where (as is usual) the air comes out at various temperatures at various parts of the exit.

If it is known that the temperature is too high although the losses are normal, one of the first matters to enquire into is the air supply.

Machines may be broadly divided into open and closed machines. The open machine gets its air from the vicinity of the shaft and throws it out by centrifugal action, no very definite path being provided for the draught. It may get too hot because the air supplied to it is too hot. This may be due to the smallness of the room in which it is run and to the failure of ventilating arrangements to change the air of the room. Sometimes the hot air from one dynamo is discharged into the space where another dynamo has its intake or the warm air from an engine may raise the temperature of the intake.

One of the commonest causes of the over-heating of open machines is the failure of the air which has been heated to get properly away. Where this is suspected it is a good plan to generate a dense volume of smoke from smouldering waste and allow it to flow from a point near the shaft of the machine outwards. The air-path is then mapped out by the smoke and one can see in what cavities it lurks and see with what velocity it is thrown out into the surrounding atmosphere. Not uncommonly in cases of over-heating one finds that the end bells of the armature conduct the air which has passed

through the armature coils back towards the centre so that it circulates over and over again, and the coils get hot because they are working in a warm atmosphére. Where this occurs the end bells must be arranged with proper spaces between them and the frame so as to allow the air to get away. It is sometimes difficult to get a proper draught through and away from the conductors of the stator, without the provision of a fan on the rotating parts, but this plan should not be resorted to until the best use has been made of the natural ventilation of the machine. Sometimes comparatively small changes in the arrangements of the parts lead to surprisingly great differences of temperature.

Enclosed machines.

When a machine is enclosed it is possible to make a measurement of the amount of air going through it. This measurement may be made either at the inlet or at the outlet. When a suitable inlet is available for measurement it has the advantage that the air there is free from eddies. Where the outlet is employed the air should be passed through a wide channel several feet long, provided with gauze baffles to make the stream lines reasonably straight.* Various ways of measuring the velocity of the air are dealt with on pp. 106 to 113.

If it should appear that the air supply is insufficient to carry away the heat losses without undue rise of temperature, this may be due either to the inefficiency of the fan or to undue obstruction in the air ducts.

Obstructed air ducts. Where a machine has been in service for some time it not uncommonly happens that the air ducts get choked up with dust. This most commonly happens where a certain amount of oil spray is allowed to escape from the bearings and mix with the ventilating air. The oil spray soaks into the dust and enables it to form a solid crust on the sides of the ventilating ducts, and may in time completely close them. Where the dust is very dry it will generally be found that it blows completely through radial ducts without lodging, especially when the draught is strong enough. The axial ducts in a revolving part may, however, accumulate dust owing to the fact that the centrifugal force presses the dust with great force on the side of the duct away from the centre, and may in time build up a deep solid cake which will almost close the duct, even though the dust is very dry and of an apparently non-caking nature. Where the dust in the radial ducts of a turbo-generator is not too much saturated with oil, it may sometimes be removed by allowing clean dry sand to be drawn into the intake and blown through the machine. This forms a sandblast against the sides of the ducts, and carries the

*See paper by Barclay and Smith on "The Determination of the Efficiency of a Turbo-Generator," *Journ. I.E.E.*, vol. 57, page 293.

loose dust with it. The method, however, is not effective where the dust is highly saturated with oil as is sometimes the case. The most effectual cure in such cases seems to be to take out the rotor and clean out the ducts by scraping the inside of the vents with a suitable shaped wire, using at the same time a powerful air blast from a nozzle. Turbo-rotors with axial ventilating ducts should always be built so that the ducts are accessible from the ends of the rotor. If it is not possible to push a scraper along the ducts from one end or the other, it may be necessary to completely disassemble the rotor before it can be cleaned out. When stators are provided with axial ventilating holes these should also be accessible from the ends for the purpose of cleaning, even when the intention is to use filtered air. The experience so far with air filters, is that they do not completely clean the air and, after running for several years, ducts in a turbo-generator may have to be cleaned out.

Where machines are provided with very small air gaps as in the case of induction motors the ventilating ducts may be closed owing to the fact that those in the rotor are not opposite those in the stator, and even when the air-gap is sufficiently large to enable the air when coming out of the rotor-ducts to get away the whole of the radial velocity is lost and this virtually may amount to such a loss of pressure as to seriously interfere with the ventilation of the machine.

Where it is found that, notwithstanding the good air-pressure given by the fan, sufficient air is not flowing through the machine, a complete investigation should be made of the pressure distribution in the air from the intake to the exit. This can conveniently be done by means of a manometer, such as illustrated in Fig. 58. To one side of the manometer is attached a long india-rubber tube, fitted with a suitable nozzle which can be fitted into various parts of the air path. If the nozzle is held so that the draught in a duct blows directly towards the mouth of the nozzle, the reading obtained on the manometer is the sum of the static pressure and the pressure due to velocity. For some purposes it is convenient to take this so that the total loss of pressure as we pass from the intake to the exit may be observed from point to point. In any part of the machine where the current of air is throttled there will be a loss of static pressure and a gain in velocity. The velocity as a rule, dissipates itself in eddies when a wider part of the channel is reached, and only a small part of it reconverted into static pressure. If the air is then passed through another place where it is throttled part of the remaining static pressure is converted into velocity and that again is dissipated, and so on to the exit. The static pressure at any point may be measured by holding the nozzle so that the draught blows across the mouth. By making a complete map of the distribution of

static and of the sum of static and velocity pressure, at each point along the air channels, some idea can be obtained of what features in the design of the channels have led to an undue drop in pressure between intake and exit.

Where the fan is itself inefficient the design of it will need to be modified. Two qualities are needed in a fan. It must, in the first place, be capable of supplying the required volume of air per second, secondly, it must be capable of supplying that volume at the pressure necessary to force it through the machine.

Defective air supply to part of machine. It may be that while the total air supplied to the machine is sufficient to carry away the total heat losses the distribution of air may be so uneven that some parts do not get their fair share and become over-heated in consequence. The investigation into the pressure distribution in the machine will generally throw light on the cause of this trouble.

Insufficient cooling surface.

Although enough air may be supplied to carry away all the heat that is produced it may be that sufficient surface is not provided to communicate the heat to the air. Where this is the case the escaping air will be much cooler than the machine itself. One does not expect to find a difference of temperature of more than 10° or 12° C. between the escaping air and the working iron with which it was last in contact if sufficient cooling surface has been provided. If there is a greater difference than this it is evidence that more air is being put through than can be heated up by the available surface.

Inefficient cooling surface.

When the ventilating ducts are very wide they may get partly coated with dirt without preventing the proper flow of air, and the air may not be properly heated up because of the non-conducting layer of dust between it and the surface of the iron.

It will be seen from the table on p. 52, that the heat conductivity of laminated iron in a direction at right angles to the surface of the laminations is only about one fiftieth as great as the heat conductivity along the punching. For this reason some designers advocate the use of longitudinal ventilating ducts made of holes punched in the iron rather than radial ventilating ducts to which the heat must be conducted across the laminations. A little consideration of the matter, however, will show that the longitudinal duct only has an advantage if the heat which arrives at the walls of the duct can be readily communicated to the air. The longitudinal ducts are commonly very rough on the inside so that the interstices soon get filled with dust, and the walls often get covered with a non-conducting layer. Under these conditions quite a high tempera-

ture may exist between the iron and the air that is passing through the ducts. Sometimes a layer of dust will collect on the lower half of the horizontal duct and form a very effective blanket. The only cure for this state of affairs is to see that the ducts are properly brushed out and that the air filter is made as efficient as possible.

One of the commonest reasons for defective heat dissipation is the presence of **thick layers of insulation** interspersed with air, as when armature-coils are insulated with tape wound rather loosely or arranged so that air is enclosed around the conductors. The stationary air acts as a very effective heat insulator and one may get very great rises of temperature in such coils even though the cross-section of copper employed would be ample if the cooling conditions were normal. In the early days of turbo-generators, end-windings of the armatures were commonly braced together for mutual support, large quantities of insulating material and binding material being used and these commonly enclosed many layers of air. In some of the early machines even with the current density as low as 1200 amps. per square inch, the temperature rise in these groups of conductors became so great as to melt the solder in the end-connectors, and this, notwithstanding the fact that a blast of air having a velocity of 5000 feet a minute, impinged directly on the insulation. In cases of this kind one may have a temperature of the coil quite low on the outside while on the inside it may be well over 100° C. The cure of course, is to separate the individual conductors as far as is possible, insulate each group with an insulation free from air spaces and arrange the air path so that it blows over the surface of the insulation.

Sometimes the conductors forming the end windings of an **armature of barrel formation** lie so close together that the air blown out from the machine cannot penetrate between them and the outer layer of the winding gets unduly hot for this reason; with a barrel type winding the length of each end-connector depends upon the amount of space allowed between the connectors, and where sufficient space has not been allowed in the original design it would be a difficult matter to obtain a better spacing without reconstructing the whole winding. Sometimes the amount of taping between conductors of the same phase is greater than it need be and some of it can be safely taken off so long as we take care to leave sufficient insulation between the phases themselves. In this way, what was originally a very badly ventilated barrel-winding can be arranged so as to get a very fair draught through it. The ventilation of a barrel winding is often improved by increasing the distance between the outer and the inner layer. This disposition of the conductors in itself permits of a reduction in the insulation.

Over-heating of armature conductors in the slots.

The heat generated in the armature-conductors in the slots can only get away either by conduction through the insulation of the armature coil or along the copper conductors to the end windings. Where a machine is of short axial length, say about 12 inches, quite a large fraction * of the heat generated in the slots can be conducted along the copper and dissipated by the end-windings. This is especially so on low voltage machines, where the end-windings are as a rule extremely cool, each conductor being only thinly insulated, and exposed to a fair draught. Where the axis of the machine is very much greater as in most turbo-generators, the greater part of the heat generated in the slot must pass through the insulation to the armature core. From the outside insulation it passes either into the iron or into the air of the ventilating ducts. It must be remembered that the temperature of the teeth of an armature is generally higher than the temperature of any other part of the iron, and that the heat can only pass from the copper to the iron when the temperature of the copper is still higher. The difference of temperature T_d between copper and iron to be expected in any particular case can be calculated in the following way:

$$T_d = \frac{\text{watts per sq. cm.} \times \text{thickness in cms.}}{\text{thermal conductivity of insulation}}.$$

The thermal conductivity of different materials is given on p. 52. The watts generated in 1 cm. length of all conductors in the slot should include eddy losses (see p. 92), and should be divided by the perimeter, taken half way between the inside and outside of the insulation to get the watts per sq. cm.

In high-voltage machines, say of 6600 or 11,000 volts, it may require a difference of temperature of 40° C. to make the heat generated in the copper flow to the iron, so that if the teeth have a temperature rise of 40° C., the temperature of the copper may be 80° C. above the surrounding atmosphere. In view of the high temperatures that may possibly be reached by armature conductors on turbo-generators owing to the augmentation of copper losses by eddy-currents, and to the great losses in the teeth, it is usual to insulate the conductors almost entirely with mica so that they can withstand the high temperature without injury. The best method of making a thorough investigation into the temperature distribution in armatures is to place thermo-junctions in the various places when the machine is being built, and bring out the wires from the junctions, so that the temperatures can be observed during the run or rapidly taken after a run at full load. As long as we are only concerned with

* See *Jour. Inst. Electrical Engineers*, vol. 59, p. 298, for method of calculating temperature distribution taking into account conduction along the copper. Also *Jour. Amer. I.E.E.*, April 1921, p. 340.

parts of the machine that are at earth potential, such as various parts of the armature iron, the matter is comparatively simple, but where we wish to take the temperature of the inside of armature coils very special precautions must be adopted to avoid the weakening of the insulation by the presence of the thermo-junction wires. Thermo-junctions in star-wound armature coils should be placed near the star-point, and that point earthed during the run.

As there are objections to the leaving of thermo-junctions inside the insulation of a high voltage machine, while it is running in normal service, it has been proposed to place the junction in between the top and bottom coils of a two layer winding. In this position it attains a temperature much nearer to that of the conductor than if it is placed outside the insulation and near the iron of the core. In the latter position it records a temperature nearer that of the iron core than that of the upper conductor. The following figures obtained by Messrs. Newbury and Fechheimer * from tests on a 12,000 K.V.A. generator are of great interest in showing the actual temperatures reached by various parts. The rating of the machine was as follows: 12,000 K.V.A., 6600-volt, 3-phase, 60-cycle, 150 revs. per min., vertical alternator. The stator had the following dimensions:

Internal diameter - -	- 192 inches.
External diameter -	- 209 inches.
Core width - - -	- 33 inches.
13 vents each - -	- ½ inch wide.
324 slots, each - -	- 0·79 in. × 3·45 in.
4 conductors per slot.	
Size of conductor - -	- 4(0·129 in. × 0·21 in.).
	4(0·162 in. × 0·25) asbestos covered.

For arrangement of conductors, see Fig. 33.
Connection, two-circuit star.
Throw of coils 1 and 7.

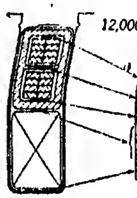
In order to make tests with thermo-junctions on the bare copper these junctions were installed in coils near the neutral point, and the neutral was earthed during the tests. Points near the centre of the machine were chosen where the temperature would be at a maximum.

In addition, thermo-junctions were installed midway between the top and bottom coil sides, and in doing this two different arrangements of slot lining were employed in order to see the effect upon

* "Some Practical Experience with embedded Temperature Detectors in large Generators." F. D. Newbury and C. J. Fechheimer. *Trans. A.I.E.E.*, vol. 39, July 1920.

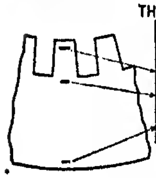
the temperature. In one arrangement the cell of the slot lining was arranged in a single piece, enveloping both coil sides as shown in Fig 34A. In the other arrangement two cells were used each enveloping only one coil side as shown in Fig. 34B. Thermo-junctions were placed in the packages of iron adjacent to the central vent. Thermo-junctions were also embedded in the iron as shown in Fig. 33. These were in the middle of a package of iron next to the central vent.

Two heat runs were made. The first at 6600 volts, 960 amperes per phase was continued until the temperatures were constant. Then without shutting down, the voltage was raised to 7260, and the



12,000 KV.-A ALTERNATOR TEMPERATURE RISES. DEGREES C.

6600 V. 9.0 A.				7260 V. 960 A.			
Max	Min.	Av.	No of Detec	Max.	Min.	Av.	
78.3	71.3	74.1	6	91.3	84.3	86.8	
77.0	70.3	73.0	6	89.0	74.7	84.0	
72.6	66.5	69.5	6	84.0	78.6	81.4	
64.0	52.9	56.9	12	69.0	57.0	63.3	Single Slot Cell
58.7	43.5	51.5	5	63.5	56.5	60.7	Double Slot Cell
54.0	42.8	47.9	6	66.3	54.2	60.1	



THERMO-COUPLES IN IRON NEAR MIDDLE OF CORE

6600 V. 960 A.				7260 V. 960 A.		
Max.	Min.	Av.	No of Detec	Max.	Min.	Av
48.0	44.3	46.3	3	60.5	53.4	56.6
49.0	40.4	45.0	3	58.3	47.1	52.3
45.1	40.5	43.0	3	53.8	50.5	52.2

ARMATURE COILS

	7260 V. 960 A.	
	Max	Min
Ends 10 Thermometers	40	35
Temp. Rise by Resistance	54.2	

Fig. 33.

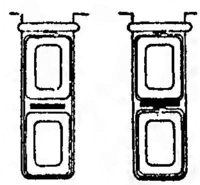


Fig. 34.

current kept constant at 960 amperes. Both runs were made at nearly zero power factor with lagging current.

The temperature rises above the ingoing air are given in Fig. 33. It will be seen that the conductors near the mouth of the slot are hotter than the others. The thermo-junctions placed between the two coil sides are from 13 to 18° C. lower in temperature than the copper of the conductor immediately above them. This is partly because the coil side in the bottom of the slot is lower in temperature than the coil side in the top of the slot and partly because the thermo-junctions in this position can never attain the average temperature of the copper above and below them. These tests are useful in showing how far temperature detectors so placed fall short of their purpose.

The ingoing air temperature was 31 deg., so that for the first heat run the highest temperature of the top coil was about 107. The calculated eddy current loss for the top coil was 48 per cent. of the I^2R loss. The I^2R loss at 0 deg. Cent. with 960 amperes per inch length of coil was 1·09 watts. The average surface (taken as bare

copper surface plus three times the distance from copper to iron) is 3·31 sq. in. The watts per sq. in. at a temperature of 107° C. were

$$\frac{(1+0{\cdot}00427\times107)1{\cdot}48\times1{\cdot}09}{3{\cdot}31}=0{\cdot}707.$$

As the thickness of the wall of insulation was 0·154 in. and its conductivity about 0·003 watts per inch cube per degree Cent. (see p. 52), the thermal drop from copper to iron to be expected was

$$\frac{0{\cdot}707\times0{\cdot}154}{0{\cdot}003}=36{\cdot}2^{\circ}\text{ C.}$$

The temperature rise of the iron 48·5° C. in the first run is taken as the mean of the maximum readings in the teeth and just back of the teeth. As part of the coil surface is exposed to air, at say 10° C. above the ingoing air, we must take the weighted mean temperature of the iron and air as follows:

$$\frac{48{\cdot}5^{\circ}\text{ C.}\times26\tfrac{1}{2}\text{ in.}+10^{\circ}\text{ C.}\times6\tfrac{1}{2}\text{ in.}}{33}=40{\cdot}8^{\circ}\text{ C. rise.}$$

The temperature of the copper of the top coil above the ingoing air which we arrive at by calculation is therefore 36·2 + 40·8 = 77° C. This agrees well with the average figure, 76° C., obtained by means of the thermo-junctions. The above calculations do not allow for the flow of heat along the conductors to the end connections. As the machine had an axial length of 33 inches, the amount of heat dissipated in this way by the centre of a coil would be small.

Where it appears that the temperature rise of a turbo-generator is too high on load, a test should be made at no load, with the excitation adjusted so as to be equal to the *resultant* excitation at full load (see vector OI_r in Fig. 212, p. 211), and the temperatures of various parts of the iron, end plates and armature copper taken after they have become nearly constant. A temperature test should then be taken with the armature conductors short-circuited (see Fig. 210, p. 209), and the field-current adjusted to give full load current in the armature. An inspection of the figures in the two cases will generally show where the trouble lies. If in the open-circuit test the armature conductors are hotter than the teeth, it shows that the armature copper is being heated up by eddy-currents due to magnetic flux across the slots (see p. 92). If the armature teeth are extremely hot, we have an indication of excessive iron loss in the teeth. If the end-plates are hot in the short-circuit run due to eddy-currents in them generated by the field around the end connections (see p. 103), it may be that the heat from these is conducted into the iron core, and leads to a rise of temperature of the core above the normal. Even when the heat from the end-plates cannot be conducted into the

core, as where a radial vent intervenes, the losses in the end-plates may contribute so much heat to the cooling air as to affect the ultimate temperature reached by other parts of the machine. It is generally found that the losses on load are about equal to the summation of the losses on open-circuit and short-circuit. Where the losses are considerably increased by eddies brought about by tooth saturation (see p. 92), the full-load loss may be even higher than the said summation.

Where the temperature of armature conductors in the slot is too high, as a rule nothing can be done to overcome the defect without making modifications in the design. An increase of the air-blast in turbo-generators may do something to cool the teeth and in that way affect the temperature rise of the armature conductors to a small degree. General high temperature of the machine, brought about by high iron loss, field-loss, or end-plate losses can be lowered by increasing the supply of cooling air.

Excessive temperature of field coils.

A field-coil gets rid of its heat either to the surrounding air or by conduction to the pole-body. The heat from the inside layers of the coil has to pass through the successive layers of copper and insulation before it can reach the exterior of the coil. Where the depth of the winding is rather great, say 2 or 3 inches, very excessive temperatures may be reached by the inside layers owing to the poor heat conduction of the layers of insulation, especially when the wire is loosely wound and contains a good deal of air space. The difference of temperature that may be expected between the inside layers and the exterior of the coil may be roughly calculated if we have available the following data :

(1) The current density in the copper.
(2) The thickness of the insulation per centimetre depth of coil and the nature of the insulation.
(3) The space factor of the winding.
(4) The ratio of the length of the bobbin to the depth of the windings.

In what follows we shall employ the following symbols :

l = length of bobbin in centimetres.

d = depth of winding in centimetres.

I_d = current density in amperes per square centimetre.

$I_s = \sqrt{\frac{l}{l+d}} I_d.$

σ = copper space factor.

i_n = thickness of insulation per centimetre of depth of winding.

k = heat conductivity of insulation in watts per square centimetre per °C. per centimetre of path.

The law of distribution of temperature takes the general form:

$$T_x = T_{\max} \cos p_1 x,$$

where $T_{\max}$ is the temperature of the hottest point measured from the artificial zero (235° below 0° C.), and T_x is the temperature of any point distant x centimetres from the hottest point along a line drawn in the direction of the flow of heat at right angles to the cooling surface, and

$$p_1 = I_r \sqrt{\frac{1 \cdot 6 \times 10^{-6} \times \sigma \times i_a}{k_h \times 235}}.$$

The value of $p_1 x$ in practice is such that $\cos p_1 x$ never assumes negative values. In table II. are given values for k_h in some typical cases founded on tests made with wire-wound coils.

TABLE II.

VALUE OF k_h FOR WIRE-WOUND COILS.

Kind of Wire	How Treated.	Diameter of Wire.	k_h
		Inches.	
Square wire double, cotton covered	Made solid with heat-conducting enamel.	0·114	0·00120 to 0·00140
Square wire double, cotton covered.	Untreated.	0·114	0·00090 to 0·00100
Round wire double, cotton covered.	Impregnated and made into solid block.	0·03 to 0·114	0·00085 to 0·00095
Round wire double, cotton covered.	Treated with enamel.	0·03 to 0·114	0·00065 to 0·00090
Round wire double, cotton covered.	Untreated, tightly wound.	0·07 to 0·114	0·00050 to 0·00060
Round wire double, cotton covered.	Untreated, tightly wound.	0·03 to 0·070	0·00040 to 0·00050
Round wire double, cotton covered.	Untreated, loosely wound.	0·03 to 0·070	0·00020 to 0·00035

The figures given in this table allow a certain margin for variations in the construction of the coil which, so far as the tests went, appeared to be sufficient for tightly wound coils. For instance, the lowest value obtained for 0·032 in. round wire double-cotton-covered and enamelled was 0·00065, and the highest value for 0·114 in. wire was 0·0009. For untreated wires both sizes averaged about ·0·00055. It is possible that the margin given should be made wider. For

loosely wound coils it will be very wide. The value of k_k is independent of the thickness of the insulation on the wire. The thickness of the insulation is taken into account in the formula in the quantity i_n, which is obtained by multiplying the number of layers per centimetre with the double thickness of cotton covering on each wire.

Example. A shunt coil is wound with 3480 turns of round double-cotton-covered wire, dia. 0·080″ bare, 0·092″ insulated. Let us first consider the case where

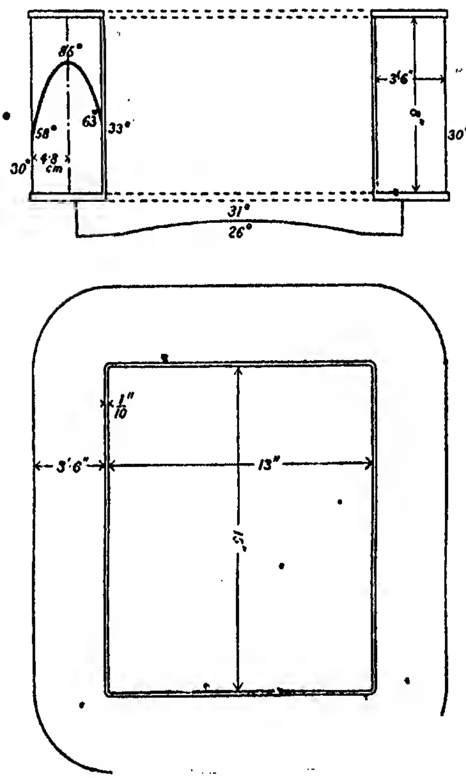


FIG. 35.—Dimensions of large shunt coil from which the temperature rise inside the coil can be approximately determined.

the coil is impregnated and made into a solid block. The dimensions of the coil are as given in Fig. 35. There are 40 layers of 87 turns each. Between the coil and the pole there is a total thickness of $\frac{1}{10}$ inch treated fullerboard, and not more than $\frac{1}{32}$ inch of air space. There is a fan on the armature which creates a breeze, which is directed by the frame in an axial direction at a velocity of 2 metres per second against the sides of the coil. The ends of the shunt coil are flanked with

fullerboard, and are disposed in such a way that the cooling of the ends may be taken as about half as good as the sides.

Find the maximum temperature rise inside the shunt coil after a long run at 1·35 amperes exciting current.

The total length of wire in the coil will be about 20,600 feet, having a resistance of 35 ohms cold, or say 40 ohms hot. The total watts lost in the coil will therefore be about 760.

The thermal resistance of a sq. cm. of the fullerboard, 0·254 cm. thick, is 180, and of the air space 150, giving a total of 330; so that we have ·003 watt conducted per sq. cm. per °C. Now calculate the cooling coefficient of the external surface. This can be done from the formula

$$h_d = \cdot 0011(1 + 0\cdot 47v^2),$$

where h_d is the heat flow in watts dissipated from 1 sq. cm. of surface for 1° C. of temperature rise above the impinging air, and v is the velocity of the air in metres per second. Here we have

$$h_d = \cdot 0011(1 + 0\cdot 47 \times 2 \times 2) = 0\cdot 0032.$$

If h_d for the ends is half this, we may conveniently take half the area at ·0032.

The cooling constant being approximately the same, we will as a first trial apportion the watts between the surfaces in proportion to their area. The areas of the various surfaces are:

	Sq. cm.	Watts taken away.
Inside surface touching pole	2900	258
Outside surface	4000	357
One end surface	1620	145
	8520	760

Now find the temperature drop through the insulation with this provisional apportionment of the total watts:

$$\frac{258}{2900} = 0\cdot 089 \text{ watt per sq. cm.} \qquad \frac{0\cdot 089}{0\cdot 003} = \text{about } 30^\circ \text{ C.}$$

If the pole were 35° C. (10° hotter than the air), this would make the inside of the coil next to the insulation 65° C. Next find the drop of temperature between outside of coil and air:

$$\frac{357}{4000} = 0\cdot 089 \qquad \frac{0\cdot 089}{0\cdot 0032} = 28^\circ \text{ C.}$$

If the air blown on the coil be taken at 30° C., this would give 58° C. for the running temperature of the exterior of the coil. Now see if this distribution of temperature will fit sufficiently well a temperature gradient curve with its apex in a suitable position to give the assumed flow of heat inwards and outwards. Let the copper space-factor be 0·6. The total thickness of cotton covering per cm.

is 0·135 cm. The value of k_h can be taken from Table II. to be 0·00095. The current density 134 amps. per sq. cm. must be multiplied by the coefficient

$$0{\cdot}83 = \sqrt{\frac{8}{8+3{\cdot}6}}$$

to allow for the cooling towards the ends of the coils. Thus we have

$$p_1 = 134 \times 0{\cdot}83\sqrt{\frac{0{\cdot}6 \times 1{\cdot}6 \times 10^{-6} \times 0{\cdot}135}{0{\cdot}00095 \times 235}} = 0{\cdot}085.$$

The law of the temperature distribution is

$$T_x = T_{max} \cos (0{\cdot}085 \times x),$$

where x is measured from the chain-dotted line Fig. 35 at a distance $x_1 = 4{\cdot}8$ cms. from the surface of the coil. This distance x_1 must be found by trial and error. In fixing provisionally the position of the apex of the temperature gradient curve, we must remember that it is the watt-shed of the coil. It marks the position of the surface inside which all heat travels inwards, and outside which all heat travels outwards. The total volume of the coil should therefore be divided by the watt-shed plane into two volumes, one of which supplies the heat travelling to the inside and the other the heat travelling to the outside. If now, in our example, we put the watt-shed surface at a distance of 4·8 cms. from the outside, we shall find that the amounts of heat generated in the volumes cut off are about in proportion to 357 and 258 respectively. We find T_{max} from

$$T_{x_1} = T_{max} \cos (0{\cdot}085 \times 4{\cdot}8),$$

where $T_{x_1} = (58^\circ + 235^\circ) = 293^\circ$. This gives us $T_{max} = 320^\circ$. $320 - 235 = 85^\circ$.

Thus the law of distribution of temperature within the coil becomes

$$T_x = (85 + 235) \cos (0{\cdot}085x).$$

From this we find that the temperature of the copper next to the internal insulation works out at 63° C. This is sufficiently near the assumed value 65 for us to accept the position taken for the apex of the curve. Fig. 35 then gives approximately the distribution of temperature under the prescribed conditions.

Next consider the case where the coil is not impregnated and is rather loosely wound, so that we may take kh at a figure as low as 0·0004. Let the depth of winding be increased to 3·7″, and the space factor be reduced to 0·585. Then

$$p_1 = 134 \times 0{\cdot}83\sqrt{\frac{0{\cdot}585 \times 1{\cdot}6 \times 10^{-6} \times 0{\cdot}135}{0{\cdot}0004 \times 235}} = 0{\cdot}129.$$

We may now take the watt-shed surface at a distance about 4·9 cms. from the outer surface, because the depth of the winding is greater than before.

The law of the temperature distribution is

$$T_x = T_{max} \cos (0{\cdot}129 \times 4{\cdot}9).$$

Now cos 1·63 = 0·81.

T_x at the surface $= (58 + 235) = 293$.

$$293 = T_{max} \times 0{\cdot}81\text{ ; therefore } T_{max} = 362. \quad (262 - 235) = 127^\circ \text{ C.}$$

This is a dangerous temperature, and would soon render the cotton covering brittle and valueless. Thus the effect of winding this coil rather loosely and not impregnating it is to cause the temperature of the internal layers to rise from 85° to 127° C. In this calculation it has been assumed that the outside of the coil is maintained at 58°; in practice the greater loss in the coil would lead to a higher temperature of the surface and a corresponding increase in the interior.

This example and the figures in Table II. serve to show how very important it is that the layers of wire in a field-coil shall be tightly wound. The matter was emphasised some years ago when machines built of a standard design were being built in two different factories *A* and *B*. The machines in factory *A* were always well within the temperature guarantee while the machines built in factory *B* were invariably above the guarantee. On making a comparison between the dimensions of the coils wound to the same specification in the two factories, it was found that in factory *B*, the space factor was considerably worse than in factory *A*, as much care not having been taken in hammering down the layers of wire. The poor space factor had two bad defects. It decreased the heat conductivity of the coil and it decreased the distance between adjacent coils so that the ventilation was not so good. Upon rewinding a set of coils in factory B, with precautions that ensured the layers lying closely together the temperature rises were reduced to the same value as those obtained in factory *A*.

Defective heat conduction towards the pole.

Sometimes the insulation put upon field-coils between the wire and the pole is much thicker than is necessary, or what is worse still, is of a kind that encloses a great number of layers of air. When this is so, the passage of heat from the inside of the coil to the pole takes place under great difficulties, and the coil may in consequence assume a temperature above its guarantee. This defect may be cured by taking off a quantity of the loose insulation and replacing it with a good reliable insulation of reasonable heat-conducting quality such as two layers of empire cloth and one layer of 0·03" leatheroid. If the pole is not wide enough to fill up the pole-space with this new insulation it may be flanked with sheet iron held in position by means of bevel-headed screws and having the corners well rounded off. The addition of this iron may also help to reduce the field-current in cases where the poles are a little saturated. Sometimes field-coils are provided with a ventilating duct between the inside of the coil and the outside of the pole. Where this is done care should be taken to see that a good draught of air is actually blown through this ventilating duct. If the arrangement of the pole is such that it is impossible to get a good draught of air through the duct it is better to fill the space up entirely with iron and rely upon the heat conductivity between the coil and the iron of the pole.

Defective surface cooling of field-coils.

It not uncommonly happens on **stationary field magnets** that the circulation of air in the vicinity of the field-coils is very poor. This is especially so on D.C. machines provided with commutating poles which nearly fill the space between the main poles. In these cases, special arrangements should be provided for creating a draught between the coils. A fairly simple plan is to direct the air which comes away from the top of the commutator necks so that it blows in an axial direction from the front or commutator end of the machine, through the field-coils to the rear. The placing of a few suitably shaped baffles fixed to the brush rocker is sufficient to effect this improvement. It must be remembered that the air coming away from the commutator necks is moving mainly in a circumferential direction, and the directing vanes must be shaped to change this tangential velocity into an axial velocity. In cases of difficulty it is best to arrange one vane between each pair of field-coils.

In the case of **revolving field-coils** where the axial length of the iron is great as compared with the pole-pitch, the temperature of the field-coils may be too high owing to defective ventilation between adjacent coils. Even where the speed of the machine is fairly high and it may appear as if the draught was fairly good, the shape of the air-space between the coils may be such as to create an eddy of air that carries the warm air round and round and does not permit of a sufficiently rapid change of air. Where the space between the coils cannot be made very great it will be found a great advantage to have a duct of fairly wide section immediately below the lower end of the field-coils. There is usually a space at the root of the poles between the lower end of the field-coils and the yoke. This space is not uncommonly filled up with a metal or wooden filling piece. In cases where the ventilation has been defective, good results have been obtained by taking out this filling piece and arranging for an air-duct which feeds air into the narrow space between the coils, the whole length of the machine thus avoiding the eddy spoken of above. Sometimes very considerable improvement may be effected in the temperature of revolving field-coils by what seem to be comparatively small changes. The mere changing of the shape of the junction between one coil and the next on strap-wound field-coils from a flat junction sticking out in a tangential direction to a flat vane arranged in a radial direction may make a difference of several degrees in the temperature rise of the coils. When no other plan is effective in reducing the temperature of the field-coils, one may resort to a fan attached to the field-spider. This fan is most effective when the vanes are arranged as scoops which slice into the almost stationary air round the field and convert it into an axial draught between the coils.

CHAPTER III.

LOW EFFICIENCY.

THE efficiency of dynamo-electric machinery is sometimes specified as the efficiency calculated from the losses measured at no load. This is common in the case where the nature of the machinery is such that the actual efficiency would be rather difficult to measure. In order to check the efficiency in these cases, all that is necessary is to measure the iron losses, copper losses, and friction and windage losses. These are added to the normal output in order to get the calculated output; then the efficiency by definition is the ratio of the output to the calculated input. This method takes no account of the stray losses which invariably occur at full load and which are generally more difficult to measure (see page 104). The efficiency calculated in this way is therefore rather higher than the actual efficiency expected.

Sometimes an attempt is made to arrive at the stray losses by measuring the losses on short-circuit and taking these, or a specified part of them, instead of the armature I^2R losses. An efficiency calculated in this way is called the "conventional efficiency" (see page 104).

Measurement of iron losses.

There are three main methods of measuring the iron loss of a dynamo-electric machine: (*a*) where the machine is driven by an independent motor, (*b*) where the machine is driven itself as a motor, (*c*) where the machine is running by its own momentum and the losses are measured by the retardation.

(*a*) **Iron Loss by Independent Motor.** A D.C. motor is direct-connected or belted to the machine whose iron loss is to be measured, and the power taken to drive the machine at normal speed at various degrees of excitation is ascertained by measuring the input to the driving motor. The measurements to be made and the method of working out the results are sufficiently indicated in Table IV., in which are given the figures for an actual test of a 600 k.w. 550-volt

machine. The losses of the driving motor at each load should be ascertained. These are entered in a column next to the total power supplied. By deducting the driving motor losses we get the net power required to drive the machine on test. Care must be taken that the brushes are rocked to the position which gives minimum driving power at full voltage (see page 252). The power taken to drive the machine at zero excitation gives the friction and windage

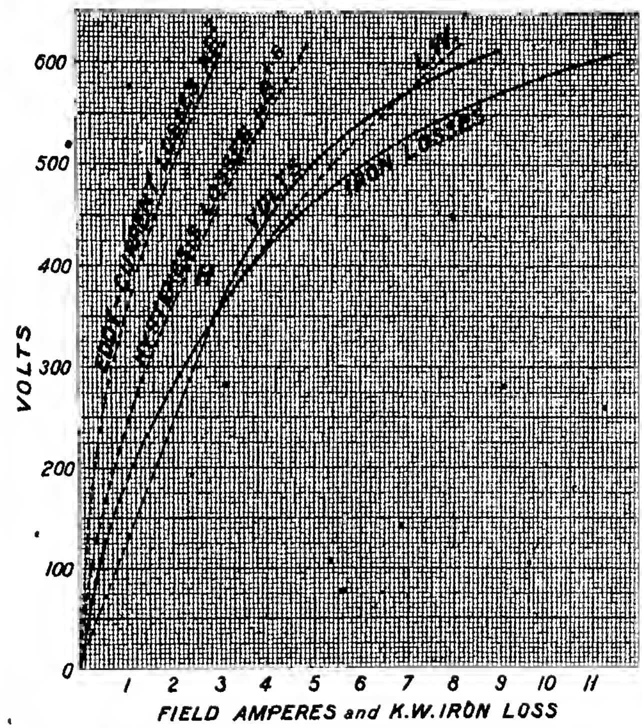


FIG. 36.—Magnetization and Iron loss curves of 600 K.W. generator showing how to find the illegitimate "iron losses" (see p. 90).

including brush friction and losses in the motor. This figure subtracted from the net driving power gives the iron loss. After taking the iron loss, the brushes are lifted off the commutator. The result is shown in the table in a fall of the driving power from 5230 to 2110 watts, showing that the brush friction was 3120 watts. After the brushes have been raised it is well to take a check reading at full excitation to see if the iron loss comes out the same as with the brushes down. Usually this check shows that the brush eddy losses are not negligible. The belt is now taken off the driving motor,

and it is found that it requires 304 watts to run the driving motor. Therefore 2110−304=1806 watts is the power lost in bearing friction and windage. If in these tests it is necessary to use a very tight belt, it is well to make some allowance for losses in the belt. Fig. 36 shows the method of plotting the magnetisation curve and iron loss curve.

TABLE IV.

IRON LOSS TEST BY INDEPENDENT MOTOR METHOD.

Speed.	600 K.W. Generator. Exciting Amps.	600 K.W. Generator. Volts.	Driving Motor. Volts.	Driving Motor. Amps.	Driving Motor. Field Amps.	Driving Motor. Watts.	Driving Motor. Motor Armature Losses.	Net Driving Watts.	Iron Losses.	Remarks.
300	0	0	110	48·6	1·99	5350	100	5250		
300	·83	100	110	52·2	1·99	5750	110	5640	390	
300	1·65	200	110	59·1	2·0	6500	140	6360	1110	
300	2·55	300	110	69·8	2·01	7670	180	7490	2240	
300	3·41	400	110	83·7	2·02	9210	260	8950	3700	
300	4·92	500	110	135·8	2·02	11680	410	11270	6020	
300	6·28	550	110	124·0	2·03	13690	560	13130	7880	
300	8·3	600	110	143	2·01	15740	740	15000	10650	
300	0	0	110	48·4	1·99	5330	100	5230		No excitation.
300	0	0	110	19·4	1·98	2140	30	2110		Brushes up.
300	0	0	110	2·86	1·97	314	10	304		Belt off.

(*b*) **Kapp Iron Loss Test.** The second method of measuring the iron loss is applicable mainly to commutating machines which can be run as D.C. motors. The test is commonly known as a Kapp iron loss test. The machine is run at normal speed with different

TABLE V.

IRON LOSS TEST BY KAPP'S METHOD.

Speed.	Armature Volts.	Armature Amperes.	Field Amperes.	$V \times I$.	I^2R. ($R = \cdot 002$.)	Power in Watts.
220	50	140	5	6990	393	6597
220	100	75·1	10·05	7510	113	7397
220	200	50·7	20·2	10150	50	10100
220	300	48·5	35·8	14550	47	14503
220	350	52·5	45·8	18350	55	18295
220	400	59·8	64·8	23900	72	23828
220	450	74·7	107·	33600	112	33488

voltages applied to the armature terminals, the excitations being adjusted so as to give the correct speed at the particular voltage applied for the time being. The product of the armature current into the armature voltage minus the I^2R losses gives the power taken to drive the machine. Thus the iron loss at normal speed at various excitations may be determined. The readings to be taken and the method of working out the results is sufficiently indicated in Table V.

The results are plotted in Fig. 37. The point where the iron-loss curve meets the abscissae line gives the friction and windage losses.

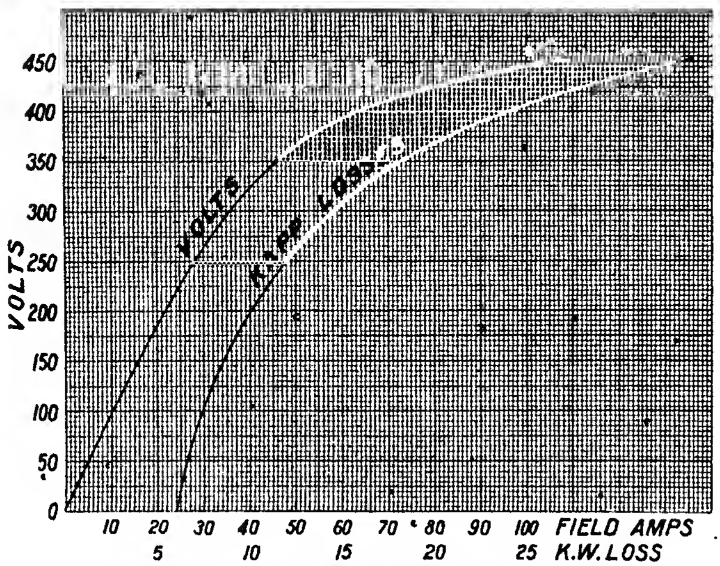


FIG. 37.—Magnetization and Iron-Loss curves obtained by Kapp Iron Loss Test.

(c) **Iron Loss by Retardation Method.** The retardation method will often be found convenient for measuring iron losses and other losses in dynamo-electric machines. It is especially useful in outdoor cases where it may be difficult to connect a driving motor. If carried out with proper precautions, very accurate results can be obtained by it. The *modus operandi* is to run the machine up to speed, let it run by its own inertia, and measure the speed from instant to instant as it is slowed down by the losses. One should have for the purpose an accurate tachometer, such as that illustrated in Fig. 8.* The tachometer must be belted to the machine with a good tight belt free from slip. The frequency at which it is necessary

* Or a stroboscopic method of speed measurement may be used (see page 77).

to take observations of the speed will depend upon the rate of deceleration. In big, high-speed machinery the deceleration on no-load is small, and it may be sufficient to take readings of speed at intervals of ten seconds. With smaller and slow-speed machines the observations may be taken every two seconds. It is a good plan to cut a piece of paper to the same curvature as the scale of the tachometer and place it over the pointer on the inner side of the scale so that the end of the pointer is visible past the edge. If the eye is then held in a position to avoid parallax, the pointer can be

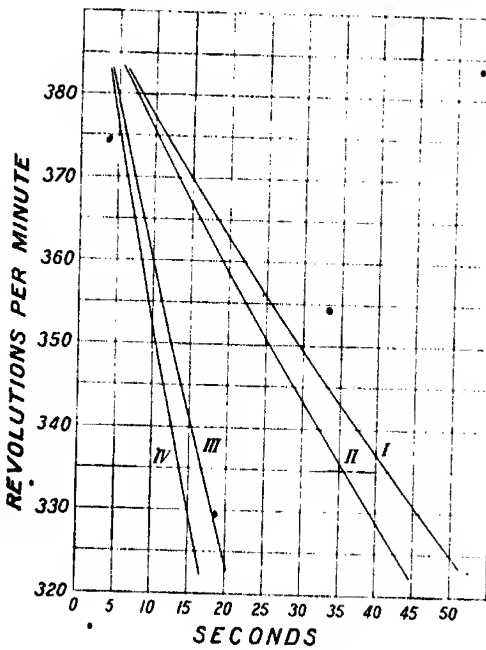


FIG. 38.—Deceleration curves at various loads.

followed closely with a point of a pencil as the speed falls, and a mark made on the paper the instant a signal is given. One observer holding a stop-watch gives signals at regular intervals, say every five seconds, by tapping on a table with a pencil at the instant that the stop-watch crosses the fifth-second mark on the watch. With a little practice the two observers can work always with the same personal error, so that the marks on the paper of the tachometer occur at a definite fraction of a second after the watch passes the fifth-second mark. After a set of observations, the speeds are read

off the tachometer scale opposite the pencil marks. The recorded figures are plotted with time as abscissae and speed as ordinates, as shown in Fig. 38. By drawing a free curve through the recorded points we obtain the speed-time curve. As a rule the recorded points do not fall exactly on the curve, owing to errors of observation but the slope of the curve at any particular point is fairly accurately ascertained. It is well to start the machine sufficiently far above normal speed so that the readings when plotted give accurately the slope of the curve at normal speed.

For machines which contain a great deal of stored kinetic energy the curves are nearly straight at normal speed, but the slope of the curve usually diminishes as the speed falls.

If M_r is the moment of inertia of the rotating part in kilograms at a metre², and ω is the angular velocity in radians per second, the kinetic energy in kilogram-metres is given by the expression

$$\frac{1}{2}\frac{M_r\omega^2}{9\cdot81}.$$

The power given out by the rotating part as it loses speed is proportional to the rate of change of this expression with regard to time. This is equal to

$$\frac{1}{9\cdot81}M_r\omega\frac{d\omega}{dt} \text{ kilogram-metres per second or } M_r\omega\frac{d\omega}{dt} \text{ watts.}$$

In converting back from kilogram-metre units to electrical units, the multiplier 9·81 comes in and cancels the 9·81 in the denominator in the first expression. If the moment of inertia of the revolving part is known, the losses expressed in watts in any particular case are obtained by finding the value of the $\frac{d\omega}{dt}$ from the slope on the curve, and multiplying by the speed expressed in radians per second and by the moment of inertia in kilograms at a metre². Fig. 38 relates to a 600 kw. 3-phase 2100-volt generator whose normal speed is 375 R.P.M. Curve I. is the deceleration curve when the machine was run unexcited, the only losses being friction and windage. The friction and windage at 375 R.P.M. amounted to 5920 watts, and the moment of inertia was 1018 kilograms at a metre². If we draw a tangent to the curve at 375 R.P.M., we find that the change of speed is 1·42 R.P.M. per second. As these units are not those used in the above formulae, we may, if we like, plot the results in radians per second as is done in Fig. 39. The slope of the curve then gives us directly the rate of change of speed in radians per second per second. Or, if we prefer to stick to the more usual shop units, we can convert from revolutions per minute to radians per second by multiplying by ·1047. Thus the rate of change of speed at 375 R.P.M. (namely

1·42 R.P.M. per second) is equal to ·1486 radians per second per secon
The speed of 375 R.P.M. is equal to $375 \times \cdot 1047 = 39 \cdot 2$ radians p
second, so that the friction and windage losses are equal to

$$1018 \times 39 \cdot 2 \times \cdot 1486 = 5920 \text{ watts.}$$

In this calculation it is necessary to know the moment of inerti
If the moment of inertia is unknown, it can be determined by takir

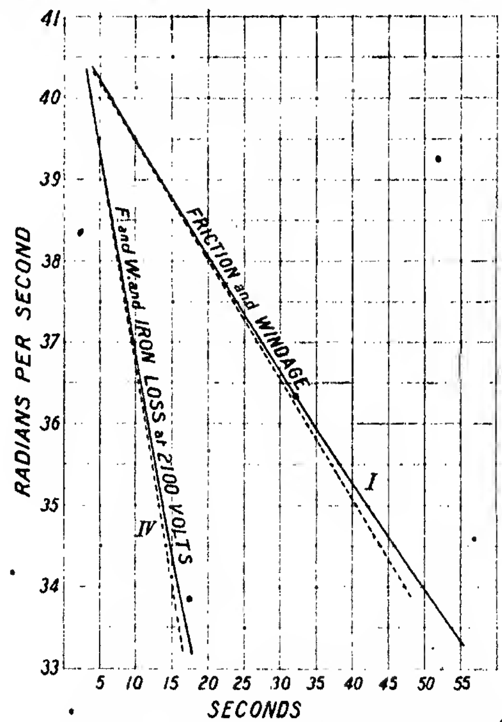


FIG. 39.—Showing method of finding the slope of a curve in radians per sec. per sec. This multiplied by the speed in radians per sec. and by M, gives the loss directly in watts.

two retardation curves at two different loads whose difference is known. To find the moment of inertia of the 600 K.W. machine, the following method might be employed. Run the machine at a low excitation, say to give 500 volts, and take the retardation curve. This is curve II., Fig. 38. Now load the 500-volt generator on a resistance rack with a known load, say 10 K.W. The load should not be made too great or the retardation will be very rapid. The load ought not to be too small or there will not be a sufficient difference in the slopes of the two curves obtained. The generator in

question excited to 500 volts and loaded with 10 K.W. will give the retardation curve III. in Fig. 38. We then have in the two cases the following expressions in which M_r and X are unknown:

$$M_r \times \omega \times \left(\frac{d\omega}{dt}\right)_{\text{II}} = X \text{ watts},$$

$$M_r \times \omega \times \left(\frac{d\omega}{dt}\right)_{\text{III}} = (X + 10{,}000) \text{ watts}.$$

Subtracting one from the other, we get

$$M_r\omega\left\{\left(\frac{d\omega}{dt}\right)_{\text{III}} - \left(\frac{d\omega}{dt}\right)_{\text{II}}\right\} = 10{,}000,$$

$$M_r = \frac{10{,}000}{\omega\left\{\left(\frac{d\omega}{dt}\right)_{\text{III}} - \left(\frac{d\omega}{dt}\right)_{\text{II}}\right\}}.$$

In this case

$$M_r = \frac{10{,}000}{39 \cdot 2\{\cdot 432 - \cdot 181\}} = 1018 \text{ kilograms at metre}^2,$$

so that by taking the difference between the two slopes at any given speed the moment of inertia of the machine in question can be determined. The value of M_r can now be filled in the expression

$$M_r\omega\frac{d\omega}{dt} = \text{watts}$$

to determine the watts lost in any retardation curve.

The friction and windage in most machines is roughly proportional to the square of the speed. When this is so, the slope of the retardation curve is proportional to the speed. The proof of this is as follows:

Let
$$M\omega\frac{d\omega}{dt} = -K\omega^2,$$

$$\frac{d\omega}{dt} = -\frac{K}{M}\omega,$$

$$\omega = C\epsilon^{-\frac{K}{M}t}.$$

The retardation curve under these conditions is an exponential curve. A D.C. generator with constant excitation and loaded on a constant resistance will carry a load proportional to the square of the speed, because both the voltage and current change with the speed. If we wish to make the retardation curve a straight line, it is necessary to adjust the load so that it is proportional to the speed. If the load on the machine is great as compared with the other losses, we can make the load proportional to the speed by connecting the machine to a resistance and keeping the current constant. The volts then vary

as the speed, and, the current being constant, the load is proportional to the speed. It is sometimes convenient to keep the load proportional to the speed in a calibration test, because by so doing we can ascertain the slope of the curve with great accuracy. The plan is to first of all make a rough determination of the friction, windage and iron losses at light excitation at various speeds, and then to make a plot of the load required at various speeds in order to make the total load vary as the speed. It is then a fairly simple matter to adjust the resistance in circuit with the generator as the speed falls so as to keep the load very nearly proportional to the speed.

Curve IV. in Fig. 38 gives the retardation curve for the 600 K.W. generator with full iron loss at 2100 volts, and friction and windage. At 375 R.P.M. the slope of this curve is 5·07 R.P.M. per second, which is equal to ·52 radians per second per second. The slope of curve I. is ·1486 radians per second per second, so that the iron loss is equal to

$$1018 \times 39 \cdot 2 \times (\cdot 52 - \cdot 1486) = 14{,}800 \text{ watts.}$$

The retardation curves can also be used for taking the losses on a short-circuit test. As the current through the armature is almost inversely proportional to the reactance (the resistance is usually small as compared with the reactance), and as the reactance falls as the speed falls, the short-circuit current at constant excitation will be almost constant over a fairly wide range of speed.

Stroboscopic method of measuring speed. One of the most accurate methods of measuring the instantaneous speed of a running machine is by the use of stroboscopic apparatus. Dr. C. V. Drysdale * and Dr. D. Robertson † have developed this method, and have provided the engineer with very convenient and accurate pieces of apparatus. The stroboscopic disc designed by Dr. Drysdale is shown in Fig. 40. This disc is attached to the end of the shaft of the machine and viewed through a rotating slit, or, as is more convenient, illuminated by the instantaneous action of a neon tube. The tube is lighted at each vibration of a standard tuning-fork, which is kept vibrating by electrical means. The layout of the apparatus is illustrated diagrammatically in Fig. 40. As the speed is increased from 50 up to 3000 R.P.M., speeds are passed through at which the square, the pentagon, or the hexagon appear to be stationary, either singly, doubly, or trebly reproduced. A

* Drysdale, C. V. "Stroboscopy," *Trans. Optical Society of London*, p. 1 (1905-6); *Optician and Photographic Trades Review*, vol. 30, p. 338 (1905-6); "Speed, Frequency, and Acceleration Measurements," *Elec. Review*, vol. 59, pp. 363 and 403 (1906).

Kennelly, A. E., and Whiting, S. E. "The Measurement of Rotary Speeds of Dynamo Machines by the Stroboscopic Fork," *Trans. Amer. Inst. Elec. Engrs.*, vol. 27, p. 631 (1908).

† Robertson, D. "The Stroboscope in Speed Measurements and other Engineering Tests," *Trans. Inst. of Engrs. and Shipbuilders in Scotland*, vol 56, p. 332 (1913); *Mechanical Engineer*, vol. 31, pp. 512 and 539 (1913).

table is provided, which tells the speed corresponding with the appearance of the stationary figure; the star in the margin is also stationary, appearing either singly or doubly, and serves to mark the speed with more precision. When the strobic disc is viewed through a revolving shutter, the table takes us up to speeds of 6000 R.P.M.

When using this apparatus in a retardation test, the best procedure is to put a circle of paper around the dial of a clock having a seconds hand; one observer gives a short sharp signal such as the

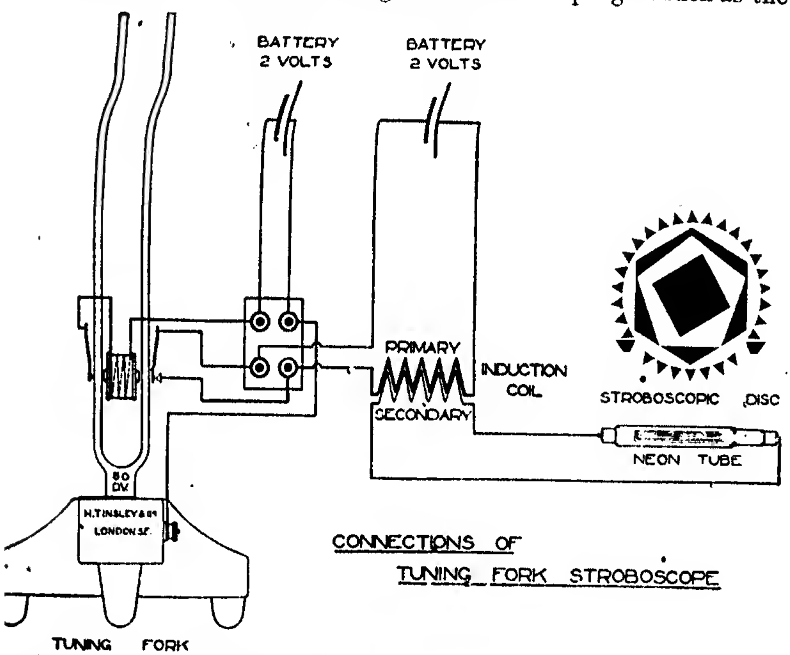


FIG. 40.—Dr. C. V. Drysdale's stroboscopic apparatus, made by H. Tinsley & Co., London.

tap of a pencil upon a table, when the stroboscope indicates a definite speed, and at the same instant another observer marks upon the paper the position of the seconds hand. In this way a number of speeds given by the stroboscope are marked off, and the number of seconds between each pair of observations can then be ascertained.

The stroboscope disc devised * by Dr. Robertson is illustrated in Fig. 41. It is fixed centrally on the end of the shaft of the machine whose speed is to be measured, and is either viewed through a shutter that opens periodically or illuminated by means of periodic flashes of light. Dr. Robertson's electrically-operated tuning-fork

* "The Separation of the No Load Stray Losses in Continuous Current Machines by the Stroboscopic Running Down Methods," Prof. D. Robertson, D.Sc., *Journ. Inst. Elec. Engineers*, vol. 53, page 308 (1915).

s shown in Fig. 41A. On the end of each prong of the fork is ttached a light aluminium wing. A slit is cut in each wing, so hat when the prongs are stationary the two slits are opposite each ther. When the fork vibrates, the slit opens twice in each cycle. n addition to the slits, the aluminium wings are provided with wo straight edges, which normally overlap. As the wings vibrate, slit opens once in each cycle. We may use the fork by eeping through the slits at the stroboscopic disc, or we may luminate the disc through the slits by means of an arc lamp and rojecting lantern. The frequency of the fork shown in Fig. 41A 83·33 *cycles per second, giving a glimpse frequency of 5000 per inute with the straight edges and* 10,000 per minute with the slits.

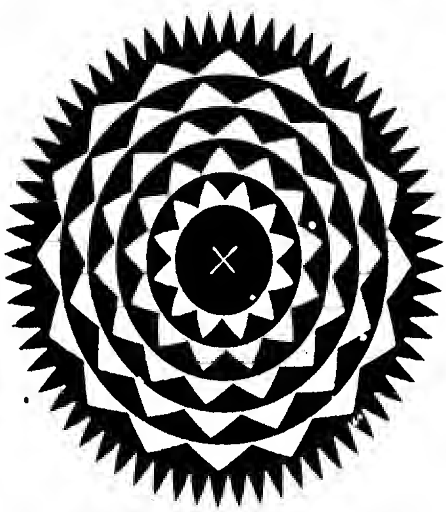


FIG. 41.—Dr. D. Robertson's stroboscopic disc.

These forks preserve their frequency with great accuracy, the errors due to accidental causes being not more than one part in 1000.

Method of measuring the speed. Confining our attention for the moment to the ring of twelve teeth in the centre of Fig. 41, we see that if the speed of the machine is such that a tooth moves exactly one tooth-pitch in the interval between two glimpses, the ring of twelve teeth would appear to be stationary. If there are 10,000 glimpses per minute and twelve teeth, the speed will be $\frac{10000}{12} = 833 \cdot 3$ revolutions per minute. This is called the *primary speed* for the 12-tooth ring. When the speed is slightly greater than the primary speed, the ring of twelve teeth appears to rotate slowly forward. When the speed is slightly less, the ring appears to rotate slowly

backwards. In general, we may say that if f_G is the number of glimpses per minute and N_S the number of spots or teeth on the ring in question, the ring will appear to be stationary at any speed equal to $m\frac{f_G}{N_S}$, where m may be any whole number, 1, 2, 3, etc. Where $m=1$, the expression gives us the primary speed for the ring having N_S teeth. Where $m=2$, a tooth moves through two tooth-pitches

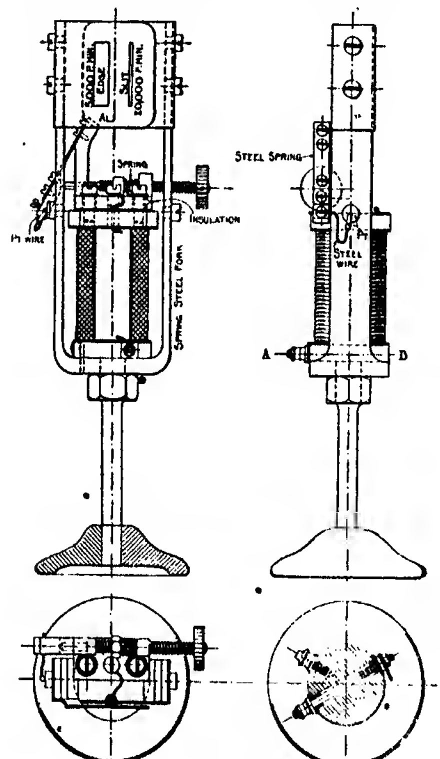


FIG. 41A.—Dr. D. Robertson's Vibrating Fork provided with slits for viewing stroboscopic effects.

in the interval between one glimpse and the next. Thus if we begin with the machine running at the primary speed, 833·3, and allow it to gradually decelerate, the ring having 13 teeth will appear stationary at 769·2($=\frac{10000}{13}$) revs. per minute; and the 14 teeth will appear to be stationary at 714·3 ($\frac{10000}{14}$) revs. per minute; and so on. When the speed is a sub-multiple of the primary speed for any particular ring, a multiple image of the ring appears, as shown in Fig. 41B. There is a double image at half the primary speed, and

a triple image at one-third the primary speed; and so on. These multiple images also appear at speeds that are whole multiples of

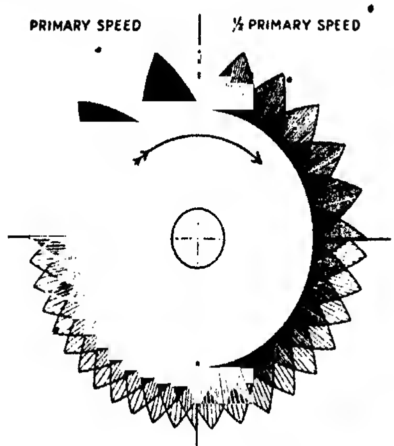


Fig. 41b.—Showing the images that appear of the 12-spot ring at the primary speed and at $\frac{1}{2}$, $\frac{1}{3}$ and $\frac{1}{4}$ of the primary speed and multiples of these.

sub-multiple speeds. Thus at a speed of $\frac{3}{2}$ times the primary speed we have a double image, because each tooth is carried $\frac{3}{2}$ pitches forward during the interval between one glimpse and the next. The method of calculating the speed at each observation will be at once understood from Table VI., abstracted from Dr. Robertson's paper, which gives the readings taken by Messrs. Rose, Sainbury and Smale in running-down tests on a D.C. machine, both with the "field on" and with the "field off."

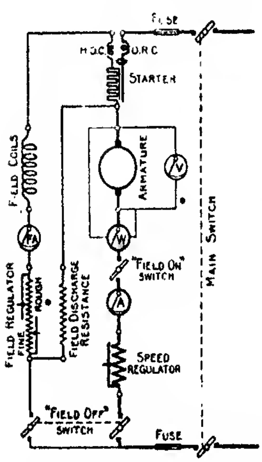


Fig. 42.

The electrical connections for these tests are shown in Fig. 42. The machine is first run as a motor from the supply mains, and the power required to overcome the friction, windage, iron loss and other no-load losses (at a certain speed, say 1200 R.P.M., and a certain excitation) is measured on the wattmeter. The speed is then raised a little, say to 1300, and the armature current is then cut off by means of

TABLE VI.

SHOWING THE VARIOUS IMAGES IN DR. ROBERTSON'S STROBOSCOPE CORRESPONDING TO VARIOUS SPEEDS.

Stroboscope.					
No. of images.	No. of times primary speed.	No. of spots in ring.	Speed R.P.M.	Field off Time in seconds.	Field on Time in seconds.
1	2	16	1250	0	0
2	3/2	12			
2	3/2	13	1154	4·4	2·2
2	3/2	14	1071	8·9	4·4
2	3/2	15	1000	13·2	6·2
2	3/2	16	937·5	16·9	8·0
1	1	12	833·3	23·3	10·9
1	1	13	769·2	27·7	12·9
1	1	14	714·3	31·6	14·8
1	1	15	666·7	34·8	16·1
1	1	16	625·0	38·0	17·6
3	2/3	12	555·6	42·9	19·9
3	2/3	13	512·8	46·6	21·2
3	2/3	14	476·2	49·4	22·8
3	2/3	15	444·4	52·2	24·1
3	2/3	16	416·7	54·6	25·1
2	1/2	12			
2	1/2	13	384·6	57·3	26·3
2	1/2	14	357·2	59·8	27·5
2	1/2	15	333·3	62·1	28·5
2	1/2	16	312·5	64·1	29·2
3	1/3	12	277·8	67·2	30·6
3	1/3	13	256·4	69·8	31·7
3	1/3	14	238·1	71·6	32·6
3	1/3	15	222·2	73·2	34·0
3	1/3	16	208·3	74·4	34·2
4	1/4	12			
4	1/4	13	192·3	76·2	—
4	1/4	14	178·6	77·4	35·8
4	1/4	15	166·7	78·9	—
4	1/4	16	156·3	80·2	37·0
4	3/4	64	117·2	84·4	—
3	2/3	64	104·2	86·0	39·3
2	1/2	64	78·1	89·1	40·9
3	1/3	64	52·1	92·2	42·0
4	1/4	64	39·1	94·0	43·2
		Stop	0	97·5	44·3

the switch marked "Field on switch." The field current is maintained constant while the armature loses speed and eventually comes to rest. The stroboscopic disc on the shaft is observed until the 16-tooth circle appears stationary and at the same instant the 12-tooth circle shows a double image, also stationary. As the primary speed for the 16-tooth circle is $\frac{10000}{16}=625$, this circle will

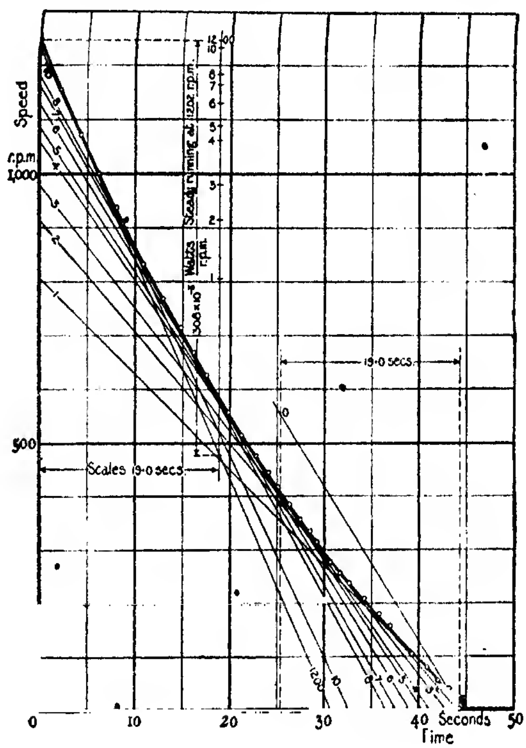


FIG. 43A.—Running-down curve with field on.

appear stationary for any whole multiple of 625 such as 1250. Now 1250 is one of the speeds that give a double image of the 12-tooth circle, because it is three times 416·7. We calculate the speed at the instant in question as follows: $\frac{10000}{16}\times\frac{2}{1}=\frac{10000}{12}\times\frac{3}{2}=1250$. After an interval of 2·2 seconds the 13-tooth circle shows a double image. The speed is then $\frac{10000}{13}\times\frac{3}{2}=1154$. After a further interval of 2·2 seconds the 14-tooth ring shows a double image. The speed is then $\frac{10000}{14}\times\frac{3}{2}=1071$; and so on, as shown in Table VI. When we get down to the speed 555·6 the 12-tooth ring shows a triple

image, because 555·6 is twice 277·8, and 277·8 is one-third of the primary speed 833·3. The quadruple images of the inner rings take us down to speed 156·3. Below that speed it is best to make our observations on the 64-tooth ring. The primary speed for this ring

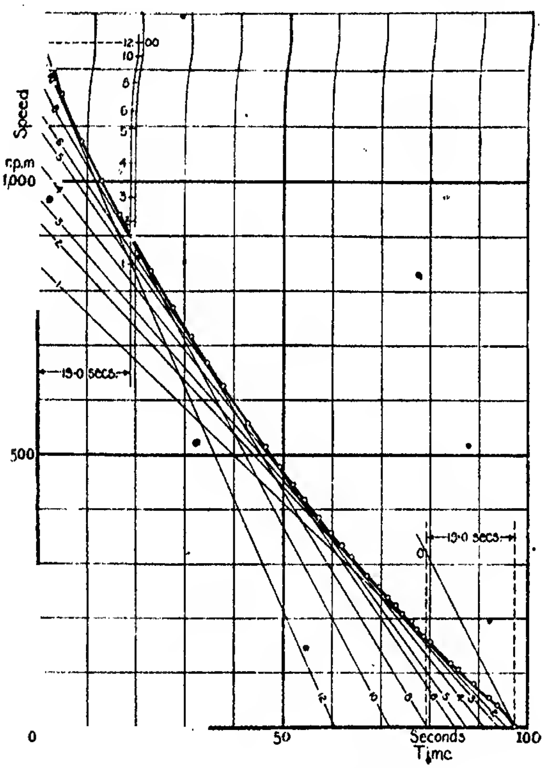


FIG. 43B.—Running-down curve with field off.

is $\frac{10000}{64}=156·3$. At 117·2 we get a quadruple image of this ring, because

$$\frac{10000}{64}\times\frac{3}{4}=117·3.$$

Then at 104·2 we get a triple image; and so on, as shown in Table VI. The observer of the stroboscopic disc gives a short sharp signal as each image becomes stationary, while a second observer records the time.

Measurement of time. The accuracy of a running-down test depends greatly upon the measurement of the time. The most

accurate instrument for this purpose is a recording drum upon whicl a mark is made electrically when a key is depressed. When thi instrument is not available good results can be obtained with a clock having a large seconds hand. By pasting on the glass a rim of paper on which the position of the hand at any instant can be marked the actual times can be read off after the test is made.

Dr. Robertson describes a very inexpensive electrical chronometer which he made by altering a Westinghouse ampere-hour meter of the shunted commutation type (Type O). A scale of 100 divisions was marked around the periphery of the disc, and a scale of disc revolutions put on the second spindle. The rest of the gearing and the shunt were removed. A series resistance was added, such as to make the speed one revolution per second when run on a 4-volt accumulator. The chronometer could be started and stopped like a stop-watch by pressing a suitable switch. With a meter of this type, the extra rotation made after switching off the current compensates for the deficiency while getting up speed. The battery should be large enough to deliver ¼ ampere throughout the duration of the test without changing its voltage. Where single intervals of time are to be measured, as distinct from obtaining a series for a whole running-down curve, this instrument is more convenient than a recording drum, and with its aid a number of repetitions of the test can be made in quite a short time.

After the deceleration curve was taken with the field on, a similar curve was taken with the field switched off, so as to measure the torque produced by friction and windage alone. The number of seconds required to sink from 1250 R.P.M. to the various speeds indicated is given in the last column.

Figs 43A and 43B show how the time-speed curves are plotted, both for the "field on" test and for the "field off" test. Tangents are drawn to the curves at convenient points, say at 0, 100, 200, 300, etc., revolutions per minute. The slopes of these tangents are proportional to the torques at the respective speeds. The torques are then plotted against speed, as shown in Fig. 43C. The scale of the torque curve is obtained from the steady reading of the watt-meter taken at 1200 R.P.M., after corrections have been made for the power lost in armature and brush resistance and in the volt coil. The paper by Dr. Robertson quoted above describes very minutely all the precautions to be taken to enable the observer to get accurate results. The clear way in which the results are worked out makes the paper of great service to anyone who wishes to make measurements of the same kind.

The paper also contains a useful synopsis of the bibliography of the subject of retardation methods.

Excessive Iron losses.

The so-called iron loss, as measured in the preceding tests, included hysteresis loss and eddy-current loss in the laminated iron, and in finger-plates, end-plates, pole-faces, and armature conductors. From an inspection of an iron-loss curve, such as that given in Fig. 36, it will be seen that in the lower stages of the magnetisation the iron loss increases in a ratio not much greater than the increase in excitation, but in the higher reaches of the curve the iron loss increases in a much greater ratio than the excitation. *It is not uncommon to find the losses increasing as the third or fourth power* of the excitation. This rapid increase of iron loss at the higher

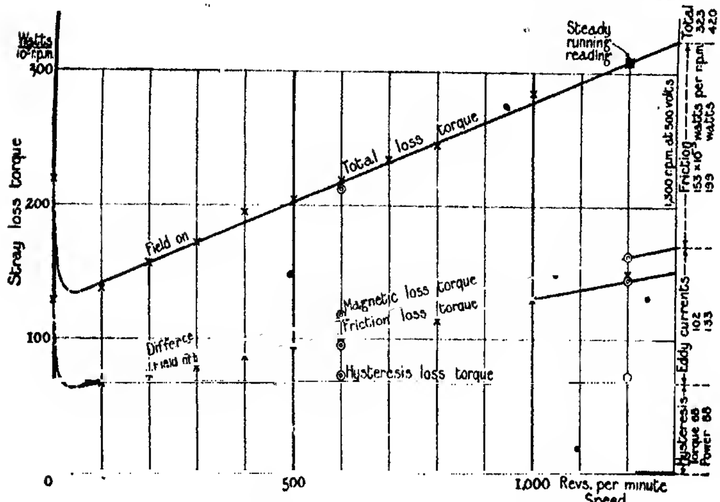


FIG. 43c. Torque-speed curves.

voltages is due to eddy-current losses which occur, not in the laminated iron, but in the end-plates, finger-plates, pole-face, and armature conductors. When we come to consider the cause of these various losses it will be seen why the increase in the ratio is so much greater than as the square of the flux-density.

It is not proposed to consider this matter as fully as one should in a book on design; it is only necessary to give the tester an idea how the magnitude of these losses depends upon the data of the machine, so that in any given case he may be able to judge whether the excessive losses occurring at no-load are probably due to hysteresis or eddy-current losses.

Separation of hysteresis and eddy-current losses.

If it is found that the iron loss at no-load is much greater than is expected from the design of the machine, it is a useful step i

finding out the cause of the trouble to separate the hysteresis loss from the eddy-current loss. This is best done by measuring the no-load losses at different speeds, exactly the same excitation being used at each of the speeds.

The excitation being the same, the flux density may be assumed to be the same,* and as the hysteresis loss varies directly as the frequency, and the true eddy-current loss as the square of the frequency, the amount of each can be determined.

An example will make the matter clear. Suppose that a 12-pole machine has a normal speed of 600 R.P.M., and at that speed and at normal excitation of 5 amperes the iron loss is 17,200 watts. It is required to divide this loss up into its hysteresis and eddy-current components. Run the machine at 300 R.P.M. with an excitation of 5 amperes and measure the loss. Let this be 6300 watts. If f is the frequency, we can write $af+bf^2=$ watts loss;

$$\therefore\ 25a+625b=6300,$$

and

$$50a+2500b=17{,}200,$$

$$b=3{\cdot}68,$$

$$a=160;$$

$$\therefore\ 160f+3{\cdot}68f^2=\text{watts loss},$$

at

$$f=50,\quad 8000+9200=17{,}200.$$

Hysteresis loss $=8000$ watts.

Eddy-current loss $=9200$ watts.

Hysteresis Loss.

The hysteresis loss depends upon the hysteretic constant of the iron, the flux-density, and the frequency. The loss per cubic centimetre is given by the expression

$$K_h\times\eta\times f=\text{watts per cubic centimetre},$$

where K_h is a coefficient depending upon the flux-density as shown by the curve in Fig. 44; η is the hysteretic constant given in Table VII.; and f is the frequency in cycles per second. In the lower reaches of the curve in Fig. 44, K_h varies as $B^{1\cdot6}$, but in the upper reaches K_h becomes constant.

If the hysteresis loss is excessive, the iron is of poor quality. This may be due to the low-grade iron having been originally employed, or to the ill-treatment of the iron during the course of manufacture. Some manufacturers drive a drift into the slots for the purpose of smoothing them on the inside. This has the effect of bending the teeth and hardening the iron. Sometimes iron which

* A rather better plan is to make the generated voltage strictly proportional to the speed. It will be found at high frequencies that the excitation has to be slightly increased to get the right voltage at the increased speed.

has had comparatively low hysteresis losses to begin with becomes "aged" after running in the machine for some time. Where the hysteresis loss is excessive, nothing can be done to cure it without

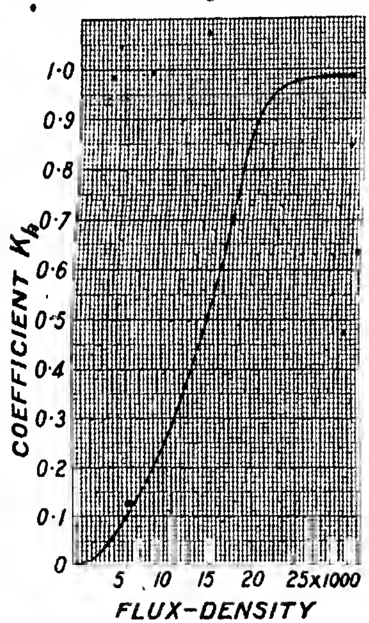


FIG. 44.

rebuilding the machine, but if the machine is still within its efficiency guarantee, it may be possible to add a fan so as to improve the ventilation and reduce any overheating due to the excessive losses.

TABLE VII.

HYSTERETIC CONSTANTS OF DIFFERENT KINDS OF IRON.

Material.	Hysteretic constant = η.
Good dynamo sheet steel - -	0·002
Fair dynamo steel - - -	0·003
Silicon steel (Si) = 4·8 per cent. -	0·00076
,, ·4 ,, -	0·001
,, ·3 ,, -	0·0016
,, 0·2 ,, -	0·0021
Cast iron - - - - -	0·011 to 0·016
Cast steel - - - - -	0·003 to 0·012

Eddy-current losses.

The eddy-current losses which occur in the laminated iron of the armature follow the law:

$$W_e = \frac{\pi^2}{6} \times \frac{1}{\rho} \times t^2 \times f^2 \times B^2_{max} \times 10^{-16} \text{ watts per cu. cm.}$$

where W_e is the eddy-current loss in a cubic cm. of iron, ρ is the specific conductivity of the iron, t is the thickness of the lamination in cms., f the frequency in cycles per sec., and B_{max} the magnetic flux density in C.G.S. lines per sq. cm. For ordinary armature iron we may take

$$\rho = 11 \cdot 7 \times 10^{-6},$$

so that the formula reduces to

$$W_e = 2 \cdot 4 \times t^2 \times f^2 \times B^2_{max} \times 10^{-11}.$$

When we measure the eddy-current loss at various excitations of a machine, we find that at the higher parts of the curve it increases in a very much greater ratio than in proportion to the square of the voltage, which is, of course, roughly proportional to the flux density in the iron. The reason for this departure from the square law is that a great part of the eddy-current loss at high voltages does not occur in the laminated iron, but in the metal fingers which support the teeth at the ends of the armature, in the end-plates, in the pole-face, and in the armature copper. At low voltages and small flux densities most of the magnetic flux from the poles finds its way along the normal flux path through the teeth and iron behind the slots. At higher voltages, however, when the flux density of the teeth becomes so great as to saturate them, the drop in magnetic potential in the teeth causes the flux to fringe at the ends of the machine and enter the finger-plates and end-plates on the flanks. The greater the saturation of the iron, the greater this effect becomes, so that while these end losses are proportional to the square of the flux density in the fingers and end-plates, the density itself increases very much more rapidly than the generated voltage. These losses in fingers and end-plates may be called illegitimate eddy-current losses.

Separation of illegitimate eddy-current losses.

The method of doing this is best shown by an example. The assumptions upon which we work are that for points below the knee of the saturation curve the hysteresis loss follows the law $B^{1 \cdot 6}$ and the eddy-current loss B^2. It is useful to have at hand a curve like that shown in Fig. 45, in which the ordinates are the abscissae raised to the power 1·6. The ordinates are given as percentages of the maximum ordinate which is 100 per cent. for a maximum abscissa of 100 per cent. If the hysteresis curve follows the law $\propto \times B^{1 \cdot 6}$, and we are given any point on the curve, we can readily plot the remainder of the curve by making use of Fig. 45.

Let us take for our example the iron loss curve of the 600 K.W. generator, particulars of which are given in Fig. 38. Take some voltage near the knee of the saturation curve just a little above the point where the curve begins to turn over, say 400 volts in this case. The iron loss for this voltage is 3700 watts, and the exciting current is 3·4 amperes. Run the machine at two different speeds at an excitation of 3·4 amperes, and separate the hysteresis loss from the eddy-current loss as shown on p. 87. Let the hysteresis loss be 2400 watts and the eddy-current 1300 watts. At 400 volts mark off 2400 watts,

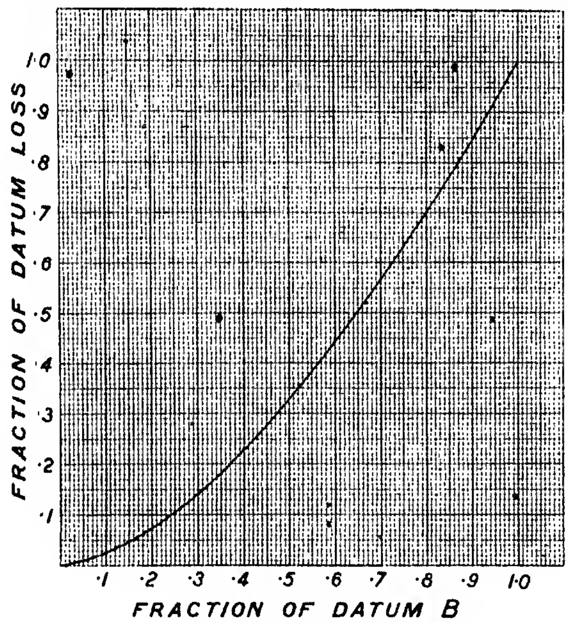


FIG. 45.—Curve for quickly calculating hysteresis losses varying as $B^{1·6}$.

as shown at the point H, and then proceed to plot the whole hysteresis loss curve on the assumption that it follows the law $B^{1·6}$. This is most readily done by the curve in Fig. 45. The voltage 300 is ·75 of 400. From Fig. 45, $B = ·75$ gives a loss of ·625; ·625 × 2400 = 1490. Set off 1490 watts at 300 volts. The voltage 200 is ·5 of 400. From Fig. 45, $B = ·5$ gives a loss of ·325; ·325 × 2400 = 780 watts. Set off 780 at the point 200, and so on for other points on the curve. The same method may be used for extrapolating for points greater than 400 on the curve. For instance, 400 is ·666 of 600. From the curve 45, when $B = ·666$, loss = ·52. 2400 ÷ ·52 = 4620. Set off 4620 watts at 600 volts, and so on for other points on the curve.

We may now proceed to plot the legitimate eddy-current loss curve on the assumption that it follows the law kB^2, and that the eddy-current loss of 1300 watts at 400 volts is legitimate eddy-current loss. At 300 volts we have $1300 \times \cdot 75 \times \cdot 75 = 734$. At 200 volts we have $1300 \times \cdot 5 \times \cdot 5 = 325$. At 500 volts we have

$$1300 \times 1\cdot 25 \times 1\cdot 25 = 2034.$$

At 600 volts we have

$$1300 \times 1\cdot 5 \times 1\cdot 5 = 2925.$$

These points are plotted on the curve marked kB^2. Now add the eddy-current losses to the hysteresis losses and we get the curve of legitimate iron losses as shown by the line marked LW. We generally find that this curve lies very closely upon the measured iron loss for all points below saturation, but that, in general, the iron losses will be very much higher than given by the LW curve at points of high saturation. The reasons for this are considered on pp. 89 and 92. Where the differences between the LW curve and the measured iron loss curve are not great we may generally assume that not much can be done to reduce the iron losses short of the provision of a better quality of iron. Where, however, we have the measured losses very much in excess of the LW losses at the higher saturations, we may take it that the losses are occurring in end-plates or in the copper conductors, and it may be possible by modifications in the machines to reduce them.

Eddy-currents in finger plates.

In turbo-generators which have very long teeth it is necessary to have very substantial fingers to prevent the laminations from fraying out end-ways and vibrating. These strong fingers are commonly made of bronze, and if the metal in them is massive, very heavy eddy-currents may be formed when the flux density in the teeth becomes great. These fingers, while being formed in a shape which gives them great strength to resist the swelling out of the punchings, should be made as thin as possible in the direction tangential to the stator working face. If the fingers have been made too massive, it is a very expensive matter to have them altered after the machine has been built.

Eddy-currents in end-plates.

Where end-plates are made of cast steel, as is sometimes necessary for mechanical strength, the eddy-currents in them may be much higher than where they are made of cast iron. The end-plates should be bevelled off as far as is consistent with mechanical strength. Eddy-current losses in end-plates on turbo-generators are not usually very great at no-load, but as we shall see later (page 103), they may be very serious at full load.

Eddy-currents in armature conductors at no load.

Where the armature conductors are fairly large, and no special precautions have been taken to eliminate these losses, they may be very considerable, and at high excitations may form a great proportion of the so-called iron losses. It is not proposed here to deal with this matter as fully as one should in a book on design; it is only necessary to give to the tester an idea of how the magnitude of these losses depends upon the dimensions and data of the machine, so that in any given case he may be able to judge whether the excessive losses occurring at no-load are probably due to these causes or not. *There are several causes of these losses: (a) the magnetic flux which passes down the slots parallel to the sides of the teeth,* (*b*) the magnetic flux which is forced out of the teeth by the saturation of the iron and has a component at right angles to the sides of the teeth, and (*c*) where the fringing flux from the sides of the poles cuts through the end windings. Eddy-currents from cause (*a*) occur when the armature conductors have considerable width in the direction tangential to the circumference of the armature, as shown in Fig. 46, and where the teeth are so highly saturated as to create a considerable difference of magnetic potential between the top and bottom of the slot. In machines where the teeth are highly saturated, care is usually taken to see that the armature conductors have no very great width in the tangential direction, so that it is not likely that one will be troubled with this effect. Eddy-currents from cause (*b*) arise when the depth of the conductors is great in a radial direction, and where the teeth are very highly saturated at the root.

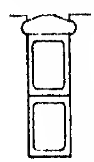


FIG. 46.

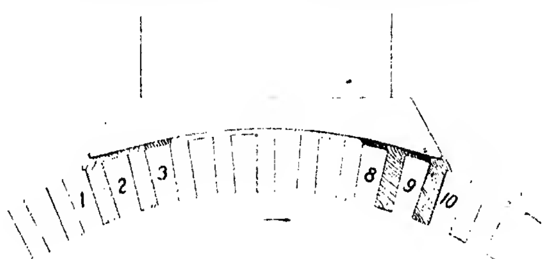


FIG. 47.

The flux being forced out, as shown in Fig. 47, cuts across the conductors in the slot. This action takes place in the most pronounced way in those slots that are just coming under or just passing from under a pole. As seen from Fig. 47, tooth No. 3 is under the body of the pole; tooth No. 2 is just under the bevel of the horn; tooth No. 1 is in a weak field. If tooth No. 3 is so highly saturated as

to require a great number of ampere-turns per centimetre, there will be a difference of magnetic potential between the sides of the slot 3-2, and flux will be driven across the slot, as indicated in the figure.

Further, as the number of ampere-turns in tooth No. 2 is much greater than in tooth No. 1, flux will be driven across the slot 2 – 1. This effect is very much greater when the machine is in load. In the case of a generator the distortion of the field in the direction of rotation will saturate tooth No. 9 very heavily, and create a flux density across the slot 9 – 10, which may in some cases be as high as 2000 C.G.S. units.

It is not uncommon for the armature conductors to have considerable radial depth; and where this is so, the eddy-current produced by the fringing flux may be very large. No satisfactory formula has yet been evolved for calculating the amount of this eddy-current with any degree of accuracy. The following formula, however, will give rough figures for the loss that may be expected per cubic centimetre of copper in the slots. The formula is based on the assumption that the zone of action of the eddy-current occurs mainly under the bevels of the pole; and it involves a term u, which stands for the ratio of the pole-pitch to the combined width of both the zones of action. The intensity of the eddy-current is proportional to the rate of change of the flux, that is, to the frequency of the machine f multiplied by u. The loss, however, is not proportional to f^2u^2, because for the greater part of the pole-pitch the flux is constant. The loss may be taken as roughly proportional to f^2u. Thus we arrive at the formula:

$$W_e = 8{\cdot}2 \times 10^{-11} \times d^2 \times f^2 \times u \times B^2,$$

where W_e is the loss in watts per cu. cm. of copper in the slot, d is the depth of the conductor in cms., and B is the flux-density produced in the middle of the conductor by the difference in magnetic potential between the two sides of the slot. It is best to take the top and bottom conductors separately. In working out the loss in the top conductor we may take the difference in the drop of magnetic potential along h_1 in tooth 9 and tooth 10 (see Fig. 48); this gives us the difference of magnetic potential between the two sides of the slot. Multiplying this by 1·257 and dividing by the width of the slot, we get B. It will in general be necessary to make a correction for the demagnetizing effect of the eddy-current. This can be done approximately as shown in the example given below. For the bottom conductor we take the difference between the drop of magnetic potential along h_2 in tooth 9 and 10 in order to get the value of B for the lower conductors.*

* A more accurate method of calculating the total flux across a slot will be found on page 157 of *Papers on the Design of A.C. Machinery*, by Hawkins, Smith & Neville.

Example.—A 350-Kw. D.C. generator had 120 slots of the size shown in *Fig. 48, each containing 6 conductors as shown. The drop in magnetic potential along* h_1 *in tooth No. 9* was 2650 ampere-turns and in tooth No. 10 it was 1400 ampere-turns. These figures can only be arrived at by a process of trial and error. The flux that leaks across the slot goes a long way to equalize the flux-densities in the two teeth; but at full load, with an armature distortion of 13,600 ampere-wires under each pole, the flux-density near the root of tooth No. 9 was driven up to 23,000, notwithstanding the leakage across the slot. The difference $2650 - 1400 = 1250$ ampere-turns tending to drive flux through the middle of the top conductors. From this we must deduct a certain amount for the demagnetizing effect of the eddy-current. The amount to deduct can be roughly determined by calculating the amount of the eddy-current, as shown below. In this case the deduction comes out at about 520, leaving 740 ampere-turns effective. Multiplying by 1·257 and dividing by the width, 1·2 cms., we get $B = 775$. In this case u could be taken at about 7. The frequency was 28. Therefore

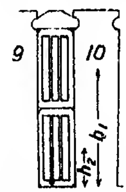


FIG. 48.—Slot and conductors. Half size.

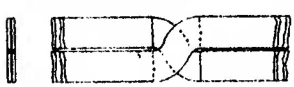


FIG. 48A.—Conductors laminated and crossed over. Half size.

$$W_e = 8{\cdot}2 \times 10^{-11} \times 4{\cdot}25 \times 784 \times 7 \times 775 \times 775 = 1{\cdot}15 \text{ watts per cu. cm.}$$

If as a first approximation we assume that the eddy-current is distributed in the conductor according to the law

$$i_d = kx,$$

where i_d is the current density at a point at a distance of x centimetres from the centre of the conductor. Then the mean loss per cubic centimetre is

$$1{\cdot}9 \times 10^{-6} \times k^2 \times x_1/3,$$

x_1 being half the depth of the conductor. In our case $x_1 = 1$, so that

$$1{\cdot}9 \times 10^{-6} \times k^2 \times \tfrac{1}{3} = 1{\cdot}15; \quad k = 1350.$$

Now the ampere-turns at the centre of the conductor due to the eddy-current are equal to $\frac{1}{2}kx_1 \times b$, where b is the total breadth of all the conductors in the slot. Therefore we have $\frac{1}{2} \times 1350 \times 1 \times 0{\cdot}77 = 520$ ampere-turns. This figure, which has been obtained by trial and error, has already been subtracted in arriving at the effective ampere-turns. There are 6200 cu. cm. of copper in the part of the top conductors lying in the slots:

$$6200 \times 1{\cdot}15 = 7150 \text{ watts.}$$

The normal loss due to the continuous load-current of 200 amperes in the same copper would be 1840 watts: but this must be augmented, owing to the fact that the current is alternating. The Field coefficient for the top conductor is 2·6 so that apart from the eddy-current due to the saturation of the teeth we have a loss of $2{\cdot}6 \times 1840 = 4700$ watts...

cooling surface of the top conductors is 21,000 sq. cm. and the thickness of the insulation is 0·17. We may therefore expect a temperature rise above the iron of

$$\frac{11850 \times 0{\cdot}17}{21000 \times {\cdot}0012} = 80^\circ \text{ C.}$$

If the temperature of the teeth is 70° C. the temperature of the top conductors may be as high as 150° C. This is sufficient to scorch the insulation. In a case very similar to the case here given the paper insulation on both sides of the top conductors was burnt quite brown while the continuation of the same insulation flanking the lower conductors was uninjured.

One way of reducing the losses under heading (*b*) is to laminate the conductors and cross over the laminations. Fig. 48A shows a method of breaking up each strap in Fig. 48 into four and crossing them over in the middle of the slot.

The no-load loss considered under (*c*) only occurs when the saturation of the teeth is so high as to cause a very heavy fringe of flux to penetrate the end windings of the armature, and when the armature conductors are of fairly great depth. It is more likely to be of importance in machines of high frequency than in machines of low frequency. No formula can be put forward to calculate these losses, the shapes of the iron paths and the disposition of the conductors making the matter rather complex. An inspection of the machine and the exercise of a little judgment is sufficient to tell us whether the losses under this heading are of importance.

Excessive copper losses.

It is not often that the resistances of armatures or field coils differ so much from the value calculated by the designer as to cause an unexpected amount of heating. Sometimes a solder joint has been badly made, and this may cause local heating to such an extent that the solder is melted and thrown out, resulting in a very high resistance, or there may be a complete open circuit. Such defects can be discovered by the methods set out on p. 36. In cases where the cross-section of copper allowed for the current is rather small, the temperature rise may be higher than was expected by the designer, with the result that the resistance is still further increased; and the heating goes on increasing according to compound interest law. Cases of overheating of armature conductors, however, when they occur, are more commonly due to defects in ventilation which are considered below.

Heating of armature conductors due to eddy-currents on load.

There are several causes of eddy-currents in armature conductors when on load. In the first place, the armature current produces a field distortion which brings about a higher state of saturation of the teeth under the leading horn of the pole in the case of a motor,

and the trailing horn of a pole in the case of a generator. This additional saturation of the teeth aggravates the no-load eddy-current loss described on p. 92. This is a very fruitful source of overheating of armature conductors, particularly on D.C. machines in which the teeth are fairly highly saturated. The existence of this loss may make itself apparent either by the overheating of the armature conductors or by the low efficiency of the machine in question. Whenever it is suspected it is well to make a lay-out of the field ampere-turns and ampere-turns, so as to ascertain the total ampere-turns on the teeth on which the ampere-turns are greatest. An example of such a lay-out is given below. A second cause of eddy-current loss in armature conductors on load is due to the magneto-motive force set up by the current in the slot which causes the magnetic flux to bridge across the slot and to penetrate the conductors, particularly those near the mouth of the slot. This source of eddy-current loss has been fully investigated by Mr. A. B. Field, who has published * curves by which the eddy-current loss in various cases can be readily calculated. In cases where eddy-current loss of this kind is suspected, it is well to calculate the amount of extra loss to be expected. The avoidance of eddy-current losses due to the magneto-motive forces within the slot is strictly a matter for the designer of the machine, and where proper provision has not been made in the design, it is impossible in most cases to remedy the defect without re-winding the machine.

Circulating currents.

When an armature is provided with several paths in parallel, it is possible under certain circumstances that circulating currents will flow around the parallel paths and cause excessive heating. One of the commonest cases that occurs in practice is the case of the multiple-wound D.C. generator provided with equalising connections, as shown in Fig. 50. If such an armature is running in a field magnet whose poles are not equally excited, circulating currents will flow in the armature conductors whose direction is such as to strengthen the weaker poles and weaken the stronger poles until the inequality between the strength of the poles is reduced to an amount just

* *Proc. Amer. Inst. Elec. Eng.*, vol. 24, p. 761, 1905. See also *Electrical World*, vol. 48, 29 Sept., 1906, where some experiments are described which corroborate the conclusions arrived at by theory. In the *Journal of the Institution of Electrical Engineers*, vol. 33, p. 1125, the matter is still further elaborated by Mr. M. B. Field, and some practical cases are considered. Eddy-current Losses in Armature Conductors, Girault, *Lumière Élect.*, 4, 35, 1908; One-sided Distribution of Alternating Current in Slots, Emde, *Elek. und Maschinenbau*, 26, pp. 703, 726, 1908; Skin Resistance Losses in Alternator Windings, F. Rusch, *Elek. und Maschinenbau*, 28, pp. 73 and 98, 1910; Eddy-currents in Solid Armature Conductors, Angermann, *Elek. und Maschinenbau*, 28, p. 975, 1910; Copper Losses in A.C. Machines, Rogowski, *Archiv für Elektrotechnik*, 2, 81, 1913; Eddy-currents in Stator Windings, H. W. Taylor, *Journ. I.E.E.*, vol. 58, p. 279, 1919.

sufficient to drive the equalising current. This matter will be more readily understood by reference to Fig. 50, which gives a diagrammatic view of a ring-wound 4-pole machine with two cross connectors AA' and BB'. We will suppose that poles 1 and 2 are strong and poles 3 and 4 are weak. It is clear that the windings under poles 1 and 2 may be regarded as the windings of a small alternator which are in parallel with the windings of another small alternator lying under poles 3 and 4, these windings being connected in parallel by means of the cross connectors. The voltage generated in the winding AB being greater than that generated in $A'B'$, the difference will drive through these windings a current which will lag with respect to the voltage in AB and lead with respect to the voltage in $A'B'$ (see Fig. 112). This current will reach its maximum when AB is nearly midway between poles 1 and 2 and will have a demagnetizing effect upon those poles. The current in $A'B'$ will reach its maximum when $A'B'$ is nearly midway between poles 3 and 4 and will have a magnetizing effect. The final difference in the strength of poles will be just sufficient to drive the equalising current. If we know the difference between the magneto-motive forces on pole 1 and pole 3, we can say positively that the circulating ampere-turns ($\times 1{\cdot}257$) on the armature are less than the difference between the magneto-motive forces.*

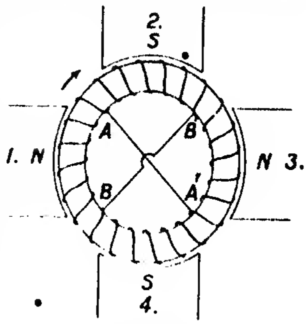


FIG. 50.

Circulating current in 3-phase mesh connected armatures.

If we have a mesh-connected armature as shown in Fig. 51 and assume that the E.M.F.'s generated in all limbs are equal and of sine-wave form, it is easy to show that the electro-motive force in phase A trying to force current one way round the triangle is exactly equal and opposite at all times to the sum of the E.M.F.'s in B and C, so that under these assumed conditions no circulating current will flow in the mesh. If all the poles of a mesh-connected armature are of exactly the same strength and the number of turns per phase is the same, the E.M.F.'s in all phases will be equal; but it does not by any means follow that the E.M.F.'s are of sine-wave form so that the

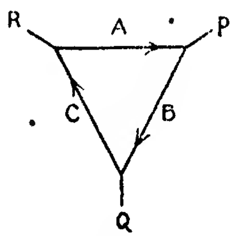


FIG. 51.

* To calculate the armature ampere-turns, see *Specification and Design of Dynamo-Electric Machinery*, pp. 286 and 598.

sum of the E.M.F.'s in B and C may not be at all times equal and opposite to the E.M.F. in phase A. Any inequality between them causes a current to flow round the mesh and this circulating current may have a very considerable influence on the efficiency and on the temperature rise. If there is a third harmonic in the phase E.M.F., the harmonics in all limbs are in phase and the total E.M.F. around the mesh has three times the amplitude of the harmonic in one phase. The total E.M.F. around the mesh can be measured by simply connecting a voltmeter in one corner of the mesh at which the connection has been opened. Fortunately, the current that flows reacts upon the field-magnet and tends to change the wave-form of the E.M.F. so as to wipe out the inequality and thus reduce the current to a minimum. The peculiarities of the wave-form of the flux distribution which tend to cause these circulating currents are necessarily diminished by armature reaction until they are just sufficient to give rise to the final value of the circulating-current. When dealing with a stationary armature it is often a simple matter to insert an ammeter at the corner of the mesh so as to measure the amount of the circulating current. It will commonly be found to have a value of 15 per cent. to 20 per cent. of the full load current of the machine, and if it is more than this it will unduly heat the copper and reduce the efficiency. The only remedy that can be applied without re-designing the whole machine is to bevel the poles so as to make the field-form distribution as near as possible to a sine-wave. When the machine is on load the distortion of the field introduces a third harmonic which increases the circulating current in the mesh. The effect of the flux wave-form upon the E.M.F. wave-form is a matter which hardly falls within the province of this book. For further information on the matter the reader is referred elsewhere.* Mesh wound machines may also have circulating currents produced in them by the inequalities in the strength of the poles. The effect is exactly similar to that described on p. 96 in connection with D.C. machines and the cure is the same.

Circulating current in 3-phase star-connected armatures.

Where a three-phase armature is star-connected any symmetrical third harmonic in the phase E.M.F. is neutralized at the terminals of the machine. Taking the positive direction along each leg of the star as from the centre outwards, the third harmonic E.M.F.'s all reach their maximum at the same instant, and are therefore opposed to one another, when considered as acting along a circuit taken from one terminal to another.

* See paper by S. P. Smith and R. S. H. Boulding, *Journ. Inst. Elec. Engineers*, vol. 53 p. 205, (1915).

Where a number of 3-phase generators are connected in parallel to the same bus bars there is no fear of a symmetrical third harmonic causing circulating currents so long as the star-points are insulated. We may earth the star-point of one machine and still be free from trouble, but if we earth two star points any inequality in the amplitude of the third harmonics of the two machines will cause circulating currents to flow. Even two exactly similar machines will as a rule have unequal third harmonics when they are loaded unequally. Higher harmonics whose order is not a multiple of three will produce circulating currents between alternators in parallel. The magnitude of these currents will in general be such as to almost wipe out the differences in the wave-forms that give rise to them.

Eddy currents in end-windings.

The currents in the end-windings of turbo-generators create an alternating magnetic field which cuts through the conductors, and if the conductors are massive or consist of flat straps whose plane is penetrated by the magnetic lines very considerable eddy-currents may be caused.

In order to form a rough estimate as to whether the losses from this cause are important in any particular case, we may adopt the following method of calculation. Draw a line to represent an imaginary magnetic path, embracing most of the conductors and cutting through the outer conductors of the tiers as shown by the thick dotted line in Fig. 52. Take the number of conductors embraced by this line (48 in Fig. 52). In a three-phase three-tier winding take two thirds of this number, multiply by the current per phase, by $\sqrt{2}$, and by 1·257 to get the total M.M.F. around the imaginary magnetic path. The M.M.F. divided by the length of the air path gives us a rough estimate of the flux density in the conductor.

If the length of the air path in Fig. 52 be taken at 80 cms. and the current per conductor at 625 virtual amperes we have

$$\text{M.M.F.} = 48 \times \tfrac{2}{3} \times 625 \times 1{\cdot}41 \times 1{\cdot}257 = 35{,}400,$$
$$B = \tfrac{35400}{80} = 443.$$

The loss per cubic centimetre of copper in the outside conductors may be taken roughly at

$$\text{Watts per cu. cm.} = 8{\cdot}2 \times 10^{-11} \times d^2 \times f^2 \times B^2,$$

where d is the depth in cms. of the conductor at right-angles to the direction of the magnetic field and f is the frequency. If we take the depth of the conductor at 2·5 cms. and the frequency at 40:

$$\text{Watts per cu. cm.} = 8{\cdot}2 \times 10^{-11} \times 6{\cdot}25 \times 1600 \times 443 \times 443$$
$$= 0{\cdot}161 \text{ watts per cu. cm.}$$

If the total volume of copper in external conductors at both ends of the machine is 15,100 cu. cm. the loss will be about 2·4 K.W. As the flux density in the next row of conductors will be only about one half, the loss will be about one quarter, or say 600 Watts, so the total will be about 3 K.W. This is by no means negligible even on a 4000 K.W. generator.

The best cure for these eddy-currents is to laminate the conductors and twist them on themselves, so that the total positive flux *enclosed is reduced to the smallest practicable amount.*

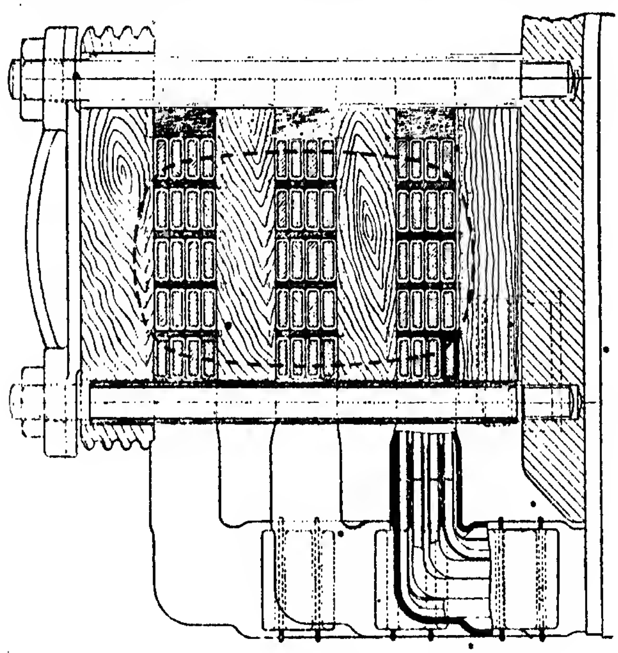


FIG. 52.

Eddy-currents in pole-faces and dampers at no-load.

At no load, although the face of the stator is at almost uniform magnetic potential, the presence of the slots causes the flux from the pole to come out in tufts towards the teeth as illustrated diagrammatically in Fig. 53. This action is most pronounced when the slots are of the open type, and where the air gap is small as compared with the width of the slots. As the pole sweeps forward the lines of force are constrained to move relatively to the surface of the iron, and will set up eddy-currents * of considerable magnitude if the pole

* See F. W. Carter, Pole-face Losses, *Journ. Inst. Elec. Engrs.*, vol. 54, p. 168.

is of solid metal. Generally it has been found that for solid machines the length of the air gap should not be less than one half the width of the slot, and even under these conditions there may be considerable loss due to eddies. If a pole is built up of laminated iron so that the resistance of the path across the face of the pole in the direction of the axis of the machine is high the eddy-currents may be very much diminished, but even in a laminated pole the eddy-currents may be excessive when the air gap is short as compared with the width of the slots and where the flux density under the teeth is high. Sometimes when copper dampers are provided, as on synchronous generators or synchronous motors, very heavy losses may occur in the dampers due to this same cause. Some manufacturers make the pitch of the damper bars equal to the pitch of the slots, in order to make all the E.M.F.'s in the bars in the same phase so that they may oppose one another. A very much better plan, however, is to skew the bars a whole slot-pitch and arrange the damper bar pitch so that there is one bar less per pole than there are slots opposite the pole. One of the best methods of detecting the presence of currents in the pole-face is to run the machine when it is quite cold and excite it very heavily for 5 or 10 minutes; then shut it down as rapidly as possible and feel the pole faces with the hand. If the pole face is found to be warmer than the field coils after this test, it is evidence of excessive eddy-currents in them. The only cure for eddy-currents in the pole face without reconstructing the machine is to increase the length of the air gap; and this cannot be done unless the field-current can be increased without exceeding the guaranteed temperature rise in the field-coils, and without causing the efficiency to be below the guarantee. In a case in the experience of the author, a machine having solid poles and provided with a damper had an air gap of 3 mms. Although the slots were semi-closed and the mouth of the slots only 4 mms., the losses in the damper at no load were very excessive. On turning down the field-magnet until the air-gap was 4·5 mms. in length the eddy-current losses were reduced from 40 K.W. to 10 K.W. The copper dampers on the poles will, as a rule, increase the eddy-current losses due to open slots. If the conductivity of the damper can be made so great that the eddy-currents in it almost wipe out the unevenness in the field distribution, the loss of the damper might be smaller than if no damper is present, but it does not appear that the amount of copper put into the damper of the ordinary commercial machine is sufficient for this purpose. In cases where there are open slots in the stator the best plan is to skew the damper rods exactly one slot pitch and insulate the damper rods with a thin covering of paper. If this is done, the E.M.F.'s set up are completely

FIG. 53.

neutralised. Another plan is to skew the armature slots by a complete slot pitch.

Eddy-currents and pole-faces and dampers on full load.

Whether a stator slot is open or closed, the current flowing in it at full load sets up a difference of magnetic potential between the adjacent teeth and tends to set up currents in any metal of the pole opposite to it. The transformer action between the conductors in the stator and the conductors in the rotor may under certain conditions be very marked. If the distribution of the current in the stator were perfectly sinusoidal so that as the pole rotated any part of it was always opposite to a stator conductor carrying the same current there would be no transformer action between the stator and rotor in a synchronous machine. Unfortunately, in 2-phase and 3-phase machines each phase-band has a considerable width and the current in the slot opposite to any given point on the pole-face varies from time to time. This change in the value of the stator current opposite to a particular part of the pole-face brings about an eddy-current in the pole-face which tends to oppose the magnetic effect of the stator current. Where the poles are solid or are provided with dampers this action may lead to undue losses in the pole face. The currents per centimetre of periphery to be expected from this course in a damper of high conductivity are not more than one-third of the current-loading per centimetre of periphery upon the armature. In most cases the damper can carry this current without excessive heating. If the damper bar is skewed by a whole stator slot pitch, or if the stator slots are skewed by a slot pitch, the eddy-current due to the variation of magneto-motive force is partly reduced. There is, however, still left the reaction of the stationary poles which are to be found superimposed upon the revolving field of most polyphase armatures. The commonest kind of three-phase armature produces a revolving field upon which is superimposed a stationary field having three poles within the span of one main pole of the machine. The amplitude of the oscillation due to those stationary poles is about 4 per cent. of the main armature magneto-motive force, the total variation of the field strength produced being 8 per cent. The best way of avoiding the production of stationary poles in a three-phase winding is to make a winding with two coil-sides per slot, and to short-chord the winding by 30°. The M.M.F. wave-form with 12 slots per pole arranged like this becomes almost sinusoidal. For further information* upon this distribution of M.M.F. on polyphase armatures, the reader is referred to a paper by Mr. B. Hague, *Jour. Inst. Elec. Engineers*, vol. 55, page 489 (1917). The higher harmonics in the armature field-form, some of which rotate in a direction opposite

* See also A. E. Clayton, The Wave-shapes obtaining with A.C. Gens., working under steady short-circuit conditions, *Jour. Inst. Elec. Engineers*, vol. 54, p. 84 (1915).

to the main field rotation, may produce quite serious losses in the pole-faces of turbo field-magnets. The provision of a damper of high conductivity will enable counter currents to flow which will almost wipe out the irregularities in the field.

Losses in end-plates on load.

The end-windings of turbo alternators set up very great alternating magneto-motive forces, which cause an alternating flux to penetrate the end-plates and end-bells and set up heavy eddy-currents.

The eddy-currents in the end-plates depend upon a number of factors, the chief of which are considered below. The shape of the end-windings and the nearness to the end-plate are important factors. Coils of the concentric type which are bent back against the end-plate produce greater losses than barrel windings which project in a direction parallel to the axis. Involute windings which are flared out at 45 degrees have an intermediate position in this respect.

A number of experiments were carried out at the College of Technology, Manchester, and at the works of the British Westinghouse Elec. and Manufacturing Co. by Messrs. M. Singer and F. E. Hill, for the purpose of ascertaining how end-plate losses vary (*a*) with the ampere-turns, (*b*) with the frequency, f, of the armature current, (*c*) with the dimensions of the coils and their position with respect to the end-plate, and (*d*) with the mean diameter of the end-plate.

The following laws were established in connection with coils of the concentric type. The losses were proportional to the square of the ampere turns and to f^{γ} where γ lay between 1·36 and 1·43.

It will probably be sufficient for our purpose to take the loss as proportional to $f^{1\cdot4}$. If A is the radial width of the coil parallel to the plane of the end-plate and B the mean distance of the coil from the surface of the end-plate the loss follows the law.

$$\text{Loss} = \frac{A}{B}a + b,$$

where a and b are constants which depended upon the size of the plate. Combining all the laws and inserting the constants so far as it was possible to ascertain them, we arrive at the following formula for the eddy-current loss in an end-plate, produced by alternating current carried in concentric 3-phase coils of the ordinary type bolted back against the end-plate.

$$\text{Loss in watts} = \left(0\cdot008D^{2\cdot1} \times \frac{A}{B} + 0\cdot32D^{0\cdot45}\right) f^{1\cdot4} \times (AT)^2 \times 10^{-8}.$$

Here D is the mean diameter of the end-plate in inches. (If this is not the same as the mean diameter of the bent-up part of the coils, it is fairer to take the mean diameter of the coil ends, because the end-plate losses are not much increased by extending the diameter of the end-plate far beyond the coils.) A is the radial width of the

concentric part of the coil parallel to the face of the end-plate and B is the mean distance of all coils from the surface of the plate. The frequency is denoted by f, and the virtual ampere turns by A.T. These are taken in a three-phase machine as number of conductors in one tier multiplied by twice the virtual current per conductor. This formula requires to be still further confirmed by additional tests, but may be taken as a fair indication of the loss to be expected.

As an example in the working out of this formula we may take *a two-pole machine with a three-tier winding of the form illustrated in Fig. 52. Let the mean diameter of the* bent-back part of the coils be 50 inches $=D$. Let $A=7$ inches and $B=7$ inches, so that $\frac{A}{B}=1$. Let $f=40$ cycles, and the virtual current per conductor be 625 amperes. Then taking 20 conductors, A.T. $=625\times20\times2=25{,}000$.

$$\text{Loss in watts} = (0{\cdot}008\times3700\times1+0{\cdot}32\times5{\cdot}8)176\times25000^2\times10^{-8}$$
$$=34600 \text{ watts in each end-plate.}$$

Losses in bolts and bracing rings. If the bolts shown in Fig. 52 which come nearest to the armature are made of steel it will be found that they will get very hot when magnetized by the alternating-current in the armature winding. It is usual to make them of bronze. Any bracing ring extending from bolt to bolt should also be made of bronze if it is near the coils. Sometimes the outer circle of bolts may be made of steel as they are not in quite such a strong field as the inner circle.

MEASUREMENT OF STRAY LOSSES.

The losses occurring in a dynamo which are not included in friction and windage losses, iron losses, and calculated copper losses in the armature and the field-magnet are often spoken of as stray losses. On account of the difficulty of measuring these that has arisen in the past, it has been customary to estimate the efficiency by some conventional method, such as the taking of the total losses as being the sum of the friction and windage, the iron losses, copper losses in the field-magnet, and the losses in the armature on short-circuit. Such an efficiency * is sometimes spoken of as the "conventional efficiency."

Short-circuit losses. There is reason to believe that the losses which occur in an armature on short circuit of an A.C. generator are not exactly the same † as the copper losses plus the stray losses

* The following rules of the American Institution of Electrical Engineers are of interest in this respect: Rules No. 422, 423, 433, 434, 435, 436, 440, 441, 442, 443, 444, 445, 458 and 459. See *Transactions of A.M.I.E.E.*, vol. 35, p. 28 (1916).

† Mr. J. A. Kuyser gives (in *Jour. Inst. Elec. Engineers*, vol. 57, p. 477) some interesting figures from which it seemed that the short-circuit stray loss appeared nearly in full during load conditions.

which occur on the machine when it is running on normal load. Sometimes the stray losses on short-circuit may be higher than the losses on normal load and sometimes the opposite may be the case. Some interesting particulars are given upon this matter in a paper by Drs. Barclay and Smith, on "Determination of the Efficiency of the Turbo Alternator." *

In a turbo generator in which the sum of the friction and windage, iron and copper losses amounted to 211 K.W. the actual measured stray losses were 141 K.W. while the stray losses on short-circuit, as determined by the American Institution of Electrical Engineers' conventional method, amounted to only 125 K.W. On a smaller machine on which the friction and windage, iron and copper losses amounted to 42·8 K.W., the actual stray losses on load amounted to 3·2 K.W., whereas the stray losses on short-circuit as determined by the A.I.E.E. conventional method amounted to 9·7 K.W. It would seem that as a rough method of determining the efficiency the rules of the A.I.E.E. bring us very much nearer the mark than if the stray losses are neglected altogether (or if, as has been proposed, only one-third of the short-circuit stray losses is added in). Nevertheless, a more accurate method is needed if the actual efficiency is to be determined.

Determination of the total losses on load from measurements of the temperature and amount of the cooling air.

In 1903 Professor R. Threlfall carried out tests on electric generators by an air calorimetry method.† The machines to be tested were totally enclosed in a wooden housing, and measurements were made on the temperature of the cooling air at the intake and the outlet, and the volume of air passing through. It was shown that the method was a practical one for the measurement of the losses occurring in the machine.

As turbo generators and many modern motors are completely enclosed, so that the amount of air passing through them can be measured, this method is very convenient for determining the losses in such machines. The precautions to be taken in a test of this kind are very fully described in the paper by Drs. Barclay and Smith referred to above. It is there shown that where proper precautions are taken the method is one of considerable accuracy. The following precautions are necessary.

Where the flow of air is measured at the outlet, the outlet should be provided with a discharge trunk like that illustrated in Fig. 54, provided with perforated metal screens for the purpose of equalising

* *Journal of the Institution of Electrical Engineers*, volume 57, p. 300, (1919).

† "The Testing of Electric Generators by Air Calorimetry," *Journal I.E.E.*, 1904, volume 33, p. 28.

the velocity of the discharge over the whole area of the outlet. Instead of perforated metal screens one might with advantage employ the honeycomb structure used in air tunnels for aeronautical work. Fig. 55 shows the great inequality in the velocity of the air at different parts of the exit when no screens were used and the great equalising effect of the screens.

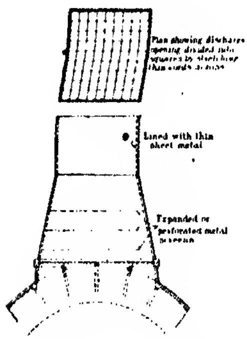


Fig. 54.—Discharge trunk for a turbo generator designed to give to the discharged air a more constant velocity over the orifice.

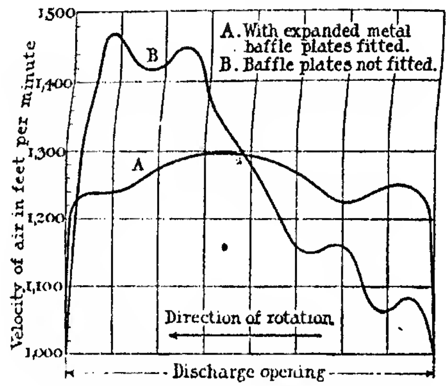


Fig. 55.—Curves showing the effect of screens in equalizing the velocity of air over the orifice.

Measurement of the temperature of a stream of air.

In taking the mean temperature of the air thrown out from the exit several precautions are necessary. It may be that the stream of air has different temperatures at different parts of its cross-section. When this is so, it is not right to take the mean of a number of thermometer readings distributed over the cross-section, unless the velocity of the stream is fairly uniform throughout the section. For if we had a higher temperature in the middle of the stream and the velocity at that part was greatest, the effect of taking the mean of a number of thermometers evenly distributed would be to give too low a figure for the mean temperature. We should make a plot of the distribution of velocity over the section of the exit and then distribute our thermometers so that the higher the velocity the greater the number of thermometers per square foot. If this distribution is carried out only approximately it will give a better result than a uniform distribution of thermometers.

Mean temperature by thermo-couples. A more convenient method of taking the mean temperature of a current of air than by the use of a large number of thermometers is to employ a number of thermo-junctions, say of iron and eureka wire, which have a straight line law. These junctions should be made from wires from the same

reels so as to ensure as far as possible that the calibrations of the junctions are the same. The length and cross-section of the wire chosen for each junction should be such that its resistance is sufficiently great to cut down the current set up by the thermo-electric effect to an exceedingly small value independently of any resistance in the voltmeter. A resistance of 1 ohm is sufficiently great, as one can see from the following: The thermo E.M.F. set up by a difference of temperature of 100° C. will be 0.0057 volt, so that the current flowing if the couple is short-circuited at the ends of the wires would be 0.0057 ampere and the power generated would be 3.2×10^{-5} watt.

This power is so excessively small that it would have no appreciable effect upon the temperature of the junction, if any ordinary precautions have been taken to make the heat conductivity of the material surrounding the junction reasonably good. If now we

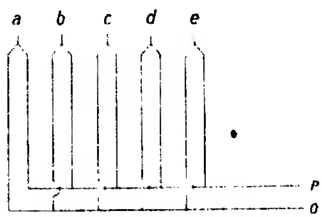


FIG. 56. Thermo-couples connected in parallel to measure the mean temperature of a current of air.

connect a number of thermo junctions in parallel, as shown in Fig. 56, and make the resistance between each junction and the common points P and O the same, the difference of potential between P and O is a measure of the mean value of the temperature rise of all the junctions above the cold junction, x, in Fig. 56. The proof of this is as follows.

Proof of the validity of the thermo-couples-in-parallel method. This is most easily proved by the superposition of electric potential systems. Let A be a network of resistances having in one of its branches an E.M.F. e_a which raises the potential of a given point of the system by the amount P_a. Let B, C, D, etc., be exactly similar networks of resistances having in other branches E.M.F.'s e_b, e_c, e_d respectively, which raise the potential of the given point to P_b, P_c, P_d, etc., respectively. Then if to a single similar system of resistances we apply at the same time all the E.M.F.'s e_a, e_b, e_c, e_d, etc., the potential of the given point will be raised by the algebraic sum of P_a, P_b, P_c, etc. Let there be n thermo-couples connected in

parallel to common points P and O (see Fig. 56). Let the resistance of the leads from P and O to each of the junctions be equal to r ohms. Let r be sufficiently great to reduce the current in each junction to a value so small that it does not affect the temperature of the junction. We will first consider the case where the resistance, R, of the voltmeter is so great as compared with r that the current taken by the voltmeter (connected across PO) can be neglected.

First raise the temperature of only one couple a, the other couples not generating any E.M.F. The resistance of the network to current from a is then $r\left(1+\frac{1}{n-1}\right)=\frac{rn}{(n-1)}$. The current which will flow is $\frac{e_a(n-1)}{rn}$. The drop in potential in the conductor carrying current to P and O is $\frac{e_a(n-1)}{n}$. Therefore the difference of potential at P and O is $e_a\left(1-\frac{n-1}{n}\right)=\frac{e_a}{n}$. Similarly, if b is acting alone it will make the difference of potential between P and O equal to $\frac{e_b}{n}$, and so with the other couples. If now all couples are acting together the difference of potential between P and O will be $\frac{e_a+e_b+e_c+\text{etc.}}{n}$, that is, equal to the mean value of e_a, e_b, e_c, etc. In practice, we have a voltmeter across P and O, which takes a small current through its resistance R. When the couple a is acting alone the volts across PO will be $e_a\frac{R}{nR+r}$. When all couples are acting together it will be $e_a+e_b+e_c$ etc. $\times\frac{R}{nR+r}$. That is to say, the small current drawn by this voltmeter produces the same percentage fall in the difference of potential between P and O as it would do if one of the thermo-couples were acting alone. It does not, therefore, affect the validity of the result. It is, however, necessary to calibrate the thermo-couple and voltmeter for any given value of R and r.

Measurement of flow of air.

The air velocity can be measured in various ways. The following may be regarded as good practical methods for this class of work. (1) The Pitot tube and allied methods; (2) The anemometer; (3) The Morris hot wire velocity indicator; (4) The Thomas Gauge and allied methods.

With the **Pitot tube** the observer measures the difference of pressure at the ends of two orifices one of which (on the dynamic tube) has its plane at right angles to the current of air and the other (on the static tube) has its plane parallel to the current of air. A good form

of Pitot tube is that illustrated in Fig. 57. Another form is shown in Fig. 58. The differences of pressure found in turbo generator work are of the order of one fifth of an inch of water. For accurate work it is necessary to employ a very sensitive form of manometer tube. The micro-manometer * designed by Mr. B. J. B. Roberts is very suitable for this work.

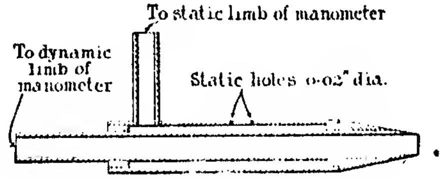


FIG. 57.

A handy form of portable micro-manometer † for use with a Pitot tube, developed by Messrs. Cramp and Frith, is shown on the right of Fig. 58. This reads directly in air velocities from 5 to 100 feet per second. For ordinary pressures the two ends of the inclined gauge are connected by rubber tubes to a Pitot tube such as shown on the left of the figure. One of the tubes of the gauge is designed

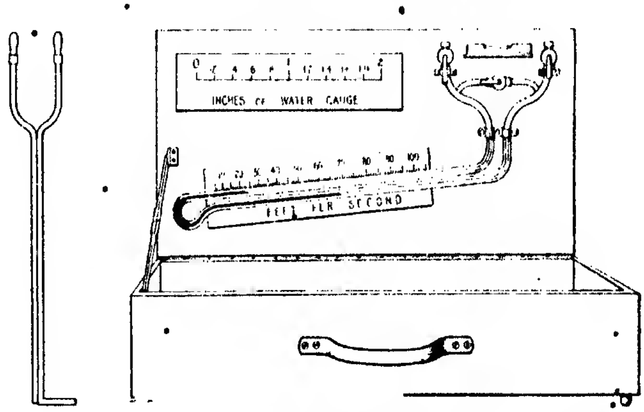


FIG. 58.—Portable micro-manometer for use with Pitot tube developed by Messrs. Cramp and Frith.

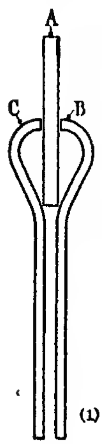
to be turned so that it faces the current of air while the other tube has the plane of its orifice set sideways to the flow of air so that the difference of pressure of the air in the two tubes is a function of the velocity. The gauge is also suitable for pressures up to 100 lb. per square inch. The whole arrangement shuts up into a box 22 in. ×

* *Proceedings of the Royal Society*, 1906, volume 78a, p. 410.

† *Journal I.E.E.*, volume 57, p. 476.

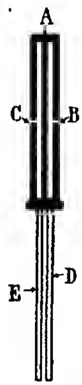
11 in. × 4 in. and is an extremely portable accurate and readily applied instrument. Messrs. Cramp and Frith also show a less portable differential gauge reading by a pointer on a disc having a double scale of from 5 to 70 feet per second air velocity, and 0 to 1 inch differential water column, by which differences of pressures of one thousandth of an inch (water gauge) can be measured.

The precautions to be taken in using the Pitot tube, and in making other measurements of velocity are fully dealt with in the paper by Barclay and Smith referred to. They point out that the principal objection to the Pitot tube for this work when making absolute measurements is that its accuracy is dependent upon the air flow being at right angles to the orifice of the dynamic tube and in the plane of the orifice of the static tube; conditions that cannot exist when the air flow is variable in direction. The fitting of a discharge trunk, as shown in Fig. 54, to the air exit greatly facilitates the accurate measurement; but no matter what precautions of this kind are taken there is still some appreciable variation of the air velocity from point to point over the discharge outlet, indicating that we do not have a pure stream line flow. With the air flow varying in direction from point to point any particular Pitot tube reading may not give accurately the velocity of that part. Dr. William Cramp* has pointed out the advantage of using the pneumometer† instead of the Pitot tube. Two forms of this instrument are illustrated in Figs. 59 and 60. The action of the instrument depends upon the condition existing upon the two sides of a disc placed at right angles to the direction of the stream whose velocity is to be measured. On the side of the disc which faces the current and close to the centre of the disc the pressure due to velocity is given by the formula $p = v^2\rho/2g$, where ρ is the density of the fluid. On the opposite side of the disc there is a negative pressure whose value is $-0{\cdot}37$ of the pressure in front. In Fig. 59 the disc A is placed at right angles to the stream and two small tubes B and C, which very nearly touch the centre, are connected to the two ends of a differential manometer. In Fig. 60 two small tubes are replaced



(1)

Fig. 59.



(2)

Fig. 60.

* *Journal I.E.E.*, volume 57, p. 479.

† *Proceedings of the Manchester Literary and Philosophical Society*, 1914, volume 58, part 2.

by small holes B and C in the centre of the discs which enclose the main disc A, forming chambers which are in communication with the manometer tubes D and E. This second form is perhaps better than the other. In either case when either tubes of the pneumometer are connected to either ends of a manometer the pressure which the latter reads is $p = 1{\cdot}37v^2\rho/2g\rho_1$, where ρ_1 is the density of the manometer fluid. The great advantage of the instrument is that inaccuracies due to variations in the static head are entirely eliminated and that the velocity is measured practically independently of any other condition.

The anemometer of the type illustrated in Fig. 61 is of great use to the dynamo tester. The best method of getting the average velocity of air with this instrument from a wide orifice is to divide the orifice up into a number of squares by stretching thin cord as shown in Fig. 54. The anemometer is then held above each square in succession for 15 or 30 seconds, being passed quickly from one square to the next without stopping to take readings. The total reading of the anemometer is taken in conjunction with the total time that it is exposed to the draught. Smith and Barclay found that when used with the precautions * which they recommend the anemometer gives reliable results.

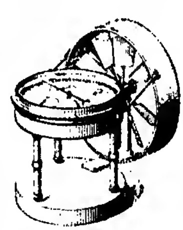


Fig. 61.

The hot-wire velocity-indicator devised by Professor J. T. MacGregor Morris is based on the fact discovered by Dr. Kennelly, and Messrs Wright and Van Bylebelt,† that with unvarying wind velocity the linear forced heat convection from a thin wire increases as the square root of the air velocity. Four exactly similar wires of material having a high electrical resistance-temperature coefficient are arranged as a Wheatstone bridge. One pair of opposite arms of the bridge is exposed directly to the air current. The other pair is also in the air current, but is protected by being enclosed in thin-walled tubes of high thermal conductivity. This small bridge is attached to the end of a tube of convenient length, and conductors are carried inside the tube to a portable battery and to a milli-voltmeter. The difference between the cooling of the arms of the bridge that are exposed to the air current and the arms that are shielded from it is indicated on the milli-voltmeter, which can be calibrated to read the air velocity directly. The indicator attains a steady reading in a few seconds and in the form described the instrument is suitable for measuring velocities up to about 2000 ft. per minute. In order that this

* *Journal of the I.E.E.*, volume 57, p. 296.

† *Transactions of the American Institution of Electrical Engineers*, 1909, volume 28, p. 363.

instrument may give accurate measurements of the flow from an orifice, it is necessary that the flow should be parallel to the axis of the trunk, Fig. 54, because any component of the velocity at right angles to the velocity has a cooling effect upon the hot wires.

Air-heating method. The flow of air through a channel can be measured by measuring the rise of temperature in it when a certain number of calories per second are imparted to it. The electrical engineer prefers to measure his heat flow in watts, taking 4·2 watts as equivalent to 1 calorie per second.

Taking the specific heat of air at 38° C. and 760 mm. pressure as 0·242, and the weight of one cubic metre of air as 1130 grams, we get the volume in cubic metres per second

$$V_m = \frac{0\cdot00212(273+T_2)\,\text{watts}}{h(T_2-T_1)} \text{ cu. metres per second,}$$

where h is the height of the barometer in millimetres and T_1 and T_2 are the temperatures in degrees centigrade before and after the

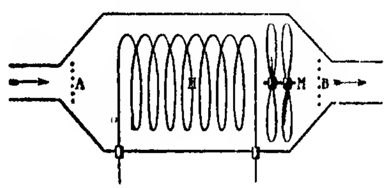


FIG. 63.

watts have been communicated to the air as heat. As there are 35·2 cu. feet in a cu. metre, the volume in cu. feet per minute,

$$V_f = \frac{4\cdot47(273+T_2)\,\text{watts}}{h(T_2-T_1)} \text{ cu. feet per minute.}$$

Barclay and Smith give the formula

$$V_f = \frac{174(273+T_2)P}{H(T_2-T_1)} \text{ cu. feet per minute,}$$

where H is the height of the barometer in inches and the power input is measured in kilowatts $=P$. In this formula a correction of $1\frac{1}{2}$ per cent. has been made for heat lost by radiation.

Several methods have been proposed for making use of this principle. One method is shown diagrammatically in Fig. 63. The air is passed through a chamber containing an electrical heater H and a suitable means for stirring up the air so as to bring it to a uniform temperature before it passes out at the exit. At the entrance a and at the exit b, a number of thermo-couples, arranged in parallel according to the scheme described on p. 107, are distributed so as to measure the difference of temperature between the air before being

heated up and after it has been heated up. The flow of air is then given by the above formula, the amount of power consumed in the heater being known.

This principle has been very well developed in the Thomas air gauge, illustrated in Fig. 64. Here the difference of temperature of the air before and after passing the heater is measured by means

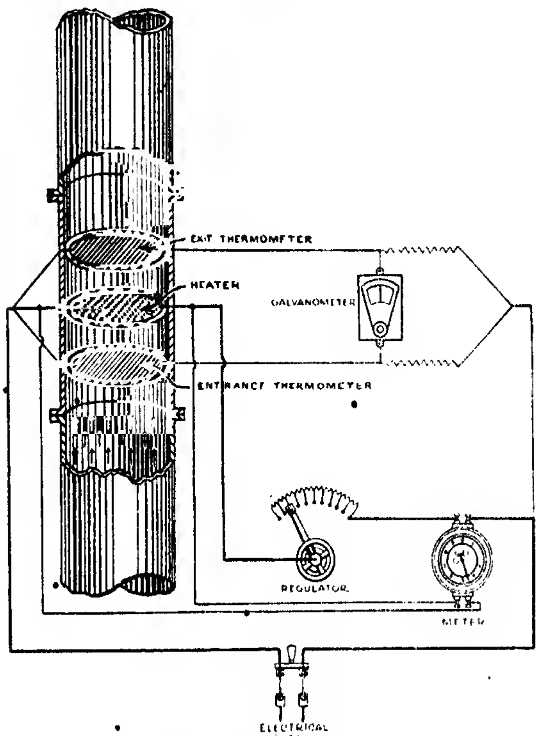


FIG. 64.—Diagrammatic view of Thomas air gauge.

of two networks of platinum wire. These gauges have been developed in various sizes for measuring the flow of gases in many commercial applications. One of these gauges could be employed either at the intake or at the exit of the cooling air of a turbo-generator.

Mr. B. R. Churcher of the Research Department of The Metropolitan Vickers Electrical Co. Ltd. has developed a very convenient Wheatstone balance by which the flow of air through a Thomas gauge can be very conveniently read off.

Another method is to **heat up the air** in the turbo-generator by the **known losses** at no-load. If the losses which go to heat up the

air * have been accurately determined by any of the methods described above, pp. 69 to 87 and the difference of temperature of the air at the intake and outlet is accurately measured, after the machine has been running for some considerable time with no losses in it, except the known losses, and the conditions have become steady, the flow of air can be calculated from the mean temperature rise $(T_2 - T_1) = t_0$ by the formula given on p. 112.

If now the machine is put on load and the supply of air is kept *at the same amount as at no-load, the mean temperature of the air*

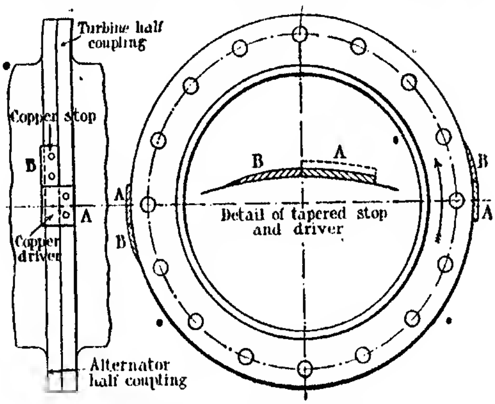


FIG. 65.—A. H. Law's coupling for running up a turbo-generator and uncoupling after it has been synchronized.

at the exit will go up to T_3. Calling $(T_3 - T_1) = t_l$, the temperature rise at full load, we have

$$\frac{\text{Losses at full load}}{\text{Losses at no-load}} = \frac{t_l}{t_0}.$$

Thus the actual losses at full load can be determined with considerable accuracy. A. H. Law has pointed out that it is possible to measure the no-load losses in a turbo-generator after it has been erected on site by running it as a synchronous motor from the bus bars, and measuring the input by watt-meters. The exciting watts can be separately measured. The bearing losses are usually small and can be measured by taking the flow of oil and its temperature rise. An allowance should be made for heat radiated from the frame. The device used by A. H. Law to run the generator up to speed, so that it could be synchronised on the bus bars and then disconnected from the steam turbine, is shown in Fig. 65. The

* The only losses which do not go to heat up the air are the bearing losses, the heat lost by radiation from the frame and by conduction to the bed plate and the energy thrown away in the velocity of the air at the discharge.

coupling bolts joining the halves of the coupling between turbine and generator were removed, and the halves of the coupling connected by two soft copper driving strips AA, riveted to the turbine half of the coupling. Each of these strips engaged with a tapered projecting stop on the alternator part of the coupling, as shown at BB. When the turbine was started AA drove BB, and the alternator was run up to speed and synchronised on the bus bars. When the turbine was shut down, B ran ahead of A, and being tapered, forced outwards *that part of A which projected over the alternator half coupling, thus freeing the alternator from the turbine.* The no-load losses in the alternator were then measured while it was running as a motor. It is also possible to measure the no-load losses by the retardation method (see p. 72). Some interesting retardation curves and temperature rise curves taken on a 5000 K.W. alternator are given by A. H. Law.*

In order to avoid the necessity of measuring the no-load losses, the heat from which is not given to the air (the bearing losses, heat radiation losses, and air velocity losses at the air discharge), Barclay and Smith have proposed the following method of finding the number of kilowatts required to raise the flow of air 1° C. When the machine is being tested the temperature rise of the cooling air is measured, (1) on open circuit with the rotor unexcited, (2) on open circuit with the rotor excited to a known value, the iron loss and rotor copper at that excitation being determined, (3) with the alternator on load.

Let t_u denote the temperature rise of the air in test (1),

t_e the temperature rise of the air in test (2),

P_c the rotor copper loss (in kilowatts) in (2),

P_i the stator loss in (2).

Then the kilowatts required to raise the air one degree are

$$\Delta P = \frac{P_i + P_c}{t_e - t_u}.$$

If t_l denotes the temperature rise in test (3), the load loss will be

$$P_l = \frac{P_i + P_c}{t_e - t_u} t_l = \Delta P \times t_l \text{ kilowatts.}$$

They have called the above method of determining the load losses the "Calibrated Air-temperature Method." It can be applied to all enclosed machinery.

Having measured with fair accuracy the **full load losses**, we may **subtract** from those the **sum of the separate losses**, consisting of the friction and windage, the iron loss at the generated voltage, and the copper losses in rotor and stator. The difference between the measured load losses and this sum gives us **the stray losses**. When we can

* *Journal of Inst. Elec. Engineers*, vol. 57, p. 306, 1919.

arrive at the approximate value of the stray losses we are in a better position to enquire into their cause. The causes of stray losses have been considered, pp. 91 to 103, and something has been said there as to the means of reducing these losses to a minimum. A great deal, however, remains to be done in investigating the causes and cures of stray losses.

It is not within the province of this book to describe the methods of finding the efficiency from the measured input and output, or by the Hopkinson method, with its important modifications by Kapp, Potier, Blondel, Hutchinson and Mordey.

These are fully dealt with in books on dynamo testing, and as the object of these tests is to find the total losses rather than to find how the losses are distributed, they are not so helpful to the engineer in finding out what is wrong as the methods described in the preceding pages.

CHAPTER IV.

MISCELLANEOUS TROUBLES.

WANT OF BALANCE.

THE rotating parts of all dynamos are given a **static balance** before they leave the makers' works, so that it is very seldom that one finds the balance as tested on rolling edges far from perfect. It is, of course, possible for a balance weight to become displaced, but that is a matter that is easily remedied. If a machine by any accident is run considerably above its rated speed, the end-windings may shift and become a little eccentric so as to disturb the balance. In order to find the high point of the end-windings, a piece of chalk may be held in the hand steadied by the frame and presented to the revolving part when running at full speed until it makes a mark on the high part. If the high part after being hammered into position is driven out again by centrifugal force, it may be necessary to re-band the winding so as to bring it tightly up against its support.

Running balance. A more common occurrence in fairly high speed machines is a defect in the running balance although the static balance is perfect. If the spider of an armature has a blow hole on the front end and the balance weight has been added at the rear end, the effect is to give to the machine a wobbling motion when running. Small defects in running balance in moderate speed machines, when noticed on the test bed at the makers' works, are often attributed to the fact that a machine is not mounted on its final foundation. It may be that after the machine has been mounted on its foundation the running balance is defective, and on commutating machines this may very seriously interfere with the collection of current at the brushes. The hints given below relating to turbo-machines are applicable to these cases except that the matter is generally much more easily dealt with when the speed is moderate.

Turbo machines. Machines designed to run at several thousand revolutions per minute require to be given a very accurate running balance in order to minimise vibration. On pages 121 to 127 below are given the outlines of the theory relating to the position of the

running centre of a simple fly-wheel where the centre of gravity is not in the geometrical centre. Every one who essays to correct the running balance of a high-speed machine should make himself familiar with these outlines, because they throw some light upon what happens at various speeds when balance weights are added to the rotor. When we are dealing with a long turbo-rotor coupled to a steam turbine, the comlepte theory is very much more complex than that given below; but although the rules here given must be taken with some reserve on that account, they nevertheless are useful in directing the general policy in the fixing of balancing weights.

The most usual way of ascertaining which way a shaft is deflecting owing to want of balance is to present to it, while it is running, the point of a blue or red pencil, held in some support secured to the stationary frame (the hand steadied* on some part of the frame is generally steady enough). The part of the shaft which is most deflected from the running centre then becomes marked with the pencil. This statement is based on the assumption that the part of the shaft in question is truly cylindrical and has its centre at the geometrical centre of the machine, when it is stationary. It sometimes happens that the parts of the shaft upon which the marks are made were not turned up at the same setting in the lathe as that at which the journals received their final finish, and these parts are slightly eccentric with the centre of the journals. When this is so the marking gives no true indication of the side that is most deflected from the running centre. Before beginning operations we must make certain that the shoulders, S, of the shaft upon which the marks will be made (see Fig. 66) are truly concentric with the journals j. The above statement is also based on the assumption that the pencil point only bears very lightly upon the part of the shaft that is most deflected. If it is pressed too severely it may make a mark most of the way around the shaft, and the place where the mark is thickest is not necessarily the place where the deflection is greatest, because the pencil gets pushed out of its position and makes the deepest mark on the place where it is being accelerated outwards. This action of the pencil always takes place to a certain extent even when the marking is extremely light, so that one must take it into account when judging the position of the greatest deflection from the position of the mark.

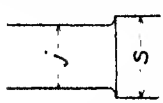


FIG. 66.

The most conspicuous phenomenon in connection with balancing turbo-rotors, is that the **position** of the maximum deflection **varies with the speed**, and in order to find out where to put the balance weight, we must understand how this maximum deflection point

* It is better to steady the hand on the top of the bearing than at the side, because the pedestal often has a sideways wobble.

varies as we gradually increase the speed from zero to a point above the critical speed. A rotor may have many critical speeds, but the one that is most commonly spoken of is the fundamental critical speed, which has the same frequency as the frequency of vibration of the rotor supported in its bearings and vibrating like a harp string giving its fundamental note. When the stiffness of the shaft and the distribution of mass on the rotor are ascertained, the critical speed is known. In practice, the stiffness of the shaft and the mass of the rotor are adjusted so that the critical speed shall be removed as far as is convenient from the normal running speed. When a machine is running at its critical speed the vibration observed is very much more intense than when it is running below or above critical speed. Sometimes it is not possible to make the shaft so stiff as to get the critical speed above the normal speed. In such cases the designer takes care that the natural fundamental frequency of vibration of the rotor is well below its normal frequency of revolution. In such cases it is of course necessary, when starting up, to run through the critical speed and if there is a considerable amount of want of balance in the rotor, very excessive vibration may be set up. Where the balance is reasonably good a machine will pass through its critical speed with only a momentary tremor. A machine designed for 3000 r.p.m. will often have its critical speed at about 2200. We know from theory that there will then be another critical speed (the second harmonic) above* 4400 and the third harmonic above 6600. But the governor is designed to cut off steam long before these speeds are reached. The facts brought out in the theory of the simple unbalanced fly-wheel may be shortly stated as follows: When the fly-wheel is running a long way below its critical speed, the point of maximum deflection is on the same side of the running centre as the centre of gravity; that is to say, the pencil makes its mark on the heavy side. When the fly-wheel is running at a speed much higher than its critical speed the point of maximum deflection is on the opposite side of the running centre to that on which lies the centre of gravity. That is to say, the pencil makes its mark on the light side. When the machine is running at its critical speed the deflection reaches its maximum, and the point of maximum deflection is 90° behind the position of the heavy point.

Fig. 67 A shows the case where the machine is running a long way below the critical speed. The marking on the shaft is represented diagrammatically by the line drawn on the outside of the circle. Fig. 67 B is a diagram of the conditions when running at the critical speed. Fig. 68 shows the conditions when running a long way above the critical speed. When running just below the critical speed the

* Owing to the shape of the turbo rotors as ordinarily constructed the second critical speed is more than twice the fundamental.

marking takes up an intermediate position between the marking on Fig. 67 A and Fig. 67 B, as shown in Fig. 69 A; and when running just a little above the critical speed the marking takes up an intermediate

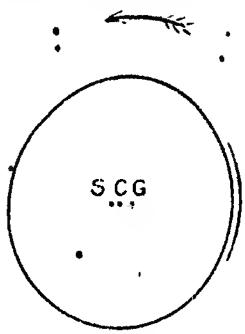


FIG. 67A.

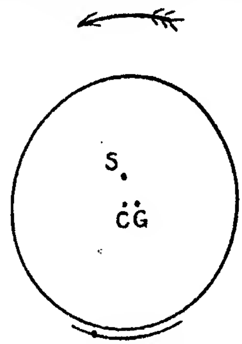


FIG. 67B.

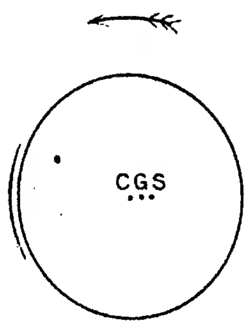


FIG. 68.

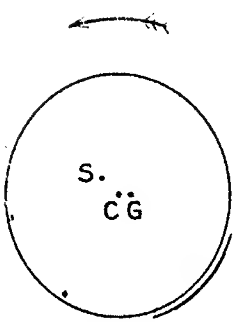


FIG. 69A.

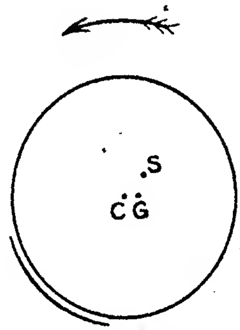


FIG. 69B.

position between the marking in Fig. 67 B and Fig. 68 as shown in Fig. 69 B. From the theory given below, it will be seen that on high speed machines having very stiff shafts the passage from the marking shown in Fig. 69 A to the marking shown in Fig. 69 B,

occurs with a change of speed of only a few revolutions per minute. That is to say, the critical period is confined within a comparatively narrow zone (see page 126).

Simple Theory of Balancing.

In dealing with the **theory of the deflection of the shaft of an unbalanced flywheel,** we are concerned with the relative positions of three centres. There is first the **geometrical centre**, or the "turned" centre, as it is sometimes called: that is to say, the centre about which the rotor revolved in the lathe in which it was finished. The position of this we will denote by C in Fig. 70. Secondly, there

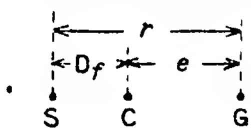


Fig. 70.

is the **centre of gravity**, which in a perfectly balanced rotor will lie in C, but whose position in general we will denote by G. And thirdly, there is the "**spinning**" **centre**, about which the rotor revolves when running at a high speed. The position of this centre changes as the speed is changed: it will be denoted by S. In general, we may take the distance CG as constant and denote it by e.

The simplest statement of the relative positions of C, G and S can be made if there are no damping forces on the shaft, for then the three centres lie in the same straight line. A more complete statement, however, requires us to take damping forces into account. We then find that S is not in general on the line CG.

Let us take the simple case first, because it brings into prominence some of the salient phenomena in the behaviour of an unbalanced rotor. We will denote the distance of G from S by r.

When the rotor is running at a **low speed**, the centrifugal force acting on G will pull C over in the direction CG, so that as in Fig. 70, S will be on the left of C. Taking CG as the positive direction, let us denote the distance SC, which is the deflection of the shaft, by D_f. Then the radius at which the centre of gravity revolves is

$$r = D_f + e.$$

If m is the mass of the rotor, the centrifugal force is

$$mr\omega^2 = m\omega^2(D_f + e),$$

where ω is the angular speed. Let the stiffness of the shaft be such that the spring force * on the rotor tending to bring C back to S

* In this simple statement we have not troubled about units. On page 124 below, the matter is re-stated and proper units are introduced.

is kD_f. In the case we have taken, this is opposite in sense to $m\omega^2(D_f+e)$; and, as we are for the moment neglecting other forces,

$$kD_f - m\omega^2(D_f+e) = 0,$$

$$(k - m\omega^2)D_f = m\omega^2 e,$$

$$D_f = \frac{m\omega^2 e}{k - m\omega^2}.$$

From this we see that when the speed is so small that $m\omega^2$ is less than k, D_f is positive; that is to say, that SC is measured from left to right and S is on the left of C as in Fig. 70. At very small speeds $m\omega^2 e$ is so small that S almost coincides with C; but as the speed increases not only does the numerator increase, but the term $m\omega^2$ also increases, and as it is to be subtracted from k it makes the denominator smaller; so that the value of D_f increases as ω increases, up to the point where $m\omega^2$ is equal to k. Then the denominator becomes zero—that is to say, D_f becomes infinite. In actual practice there are damping forces which save the situation; but if there were no damping forces the shaft would break at a speed which made $m\omega^2$ equal to k. This is the whirling speed, or the speed of resonance. In the design, k and m must be adjusted so that the speed of resonance is far removed from the normal speed of the machine.

If we now have $m\omega^2$ greater than k, we see that D_f is negative—that is to say, SC is measured from right to left, as in Fig. 71.

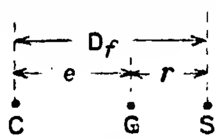


FIG. 71.

If $m\omega^2$ is only a very little bigger than k, the denominator is very small—that is to say, D_f is very great. As the speed is further increased, the denominator becomes greater, and D_f becomes smaller, until in the limit $m\omega^2$ becomes so great in comparison with k that we may neglect k, and write

$$D_f = \frac{m\omega^2 e}{-m\omega^2} = -e.$$

At very high speeds SC is negative and equal to e, so that S coincides with G. That is to say, at high speeds the rotor revolves about its own centre of gravity, bending the shaft by a constant amount e in order to do this. At the very highest speeds the restoring force ke can be neglected in comparison with the centrifugal forces. As the speed is lowered a little, the force ke does affect the amount of deflection of the shaft; but it makes it greater instead of

smaller, because the speed is so great that the deflection produced by ke lags 180° in phase behind the force. As the speed is lowered, the added deflection due to this cause becomes greater and greater, until the resonance point is reached. Below the resonance point the force ke acts in opposition to the force $m\omega^2$, until at the lowest speed it brings back S almost to C, the "turned" centre.

Theory of deflection of shaft, taking damping forces into account. In actual practice we can run a turbo rotor at the speed of resonance without breaking the shaft, if the balance is not excessively bad. The vibration is often very severe at this speed, but the deflection is kept within bounds by damping forces, acting for the most part on the journals. These forces on the journals are mainly fluid-frictional forces, which take energy out of the vibrating rotor. They may for the present discussion be taken as proportional * to the velocity of vibration. Sometimes there are energy-absorbing forces within the rotor itself, as where a rotor is built up of plates which move relatively to one another as the shaft bends.

When we introduce the damping forces we must be prepared to find that S is no longer in the line CG; so the problem becomes a two-dimensional one. It can, however, be very much simplified by resolving the motion of C and G around S into a horizontal and a vertical motion. As these two motions are exactly similar, except that they differ in phase by 90°, we may consider the horizontal component of the motion and make up our differential equation as if the motions of C and G with regard to S were motions of translation only.

First we must get an expression for the motion of translation of G with regard to C. As C and G revolve about S they of course revolve about each other. Consider for the moment C as a centre about which G revolves, and let us begin to count time from the instant when G is immediately to the right of C, as in Fig. 72. We

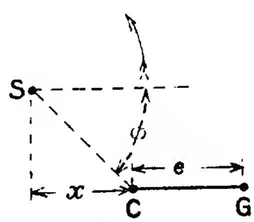


FIG. 72.

* Any energy-absorbing forces that are not proportional to the velocity will also damp the vibration. The theory would be affected in so far that b would not be a constant, so that the shape of the deflection-graph would be altered; but the conclusions would not be affected for practical purposes, provided we give to b its approximate value at critical speed.

make no assumption, of course, as to the position of S at this moment. The distance of G to the right of C at any instant is then given by the expression $e\cos\omega t$, where t is the number of seconds that have elapsed since we began to count time. Now denote by x the distance of C to the right of S. At any instant x may be positive or negative, but always the distance of G to the right of S will be $(x+e\cos\omega t)$. If m is the mass acting at G, the force due to the horizontal acceleration of G will be

$$m\times\frac{d^2(x+e\cos\omega t)}{dt^2}=m\ddot{x}-me\omega^2\cos\omega t.$$

Let the horizontal damping force be proportional to the horizontal velocity of $G=b\dot{x}$. Let the stiffness of the shaft be such that the horizontal spring-force tending to restore C is kx; then

$$m\ddot{x}+b\dot{x}+kx=m\omega^2e\cos\omega t,$$

$$x=\frac{m\omega^2e}{\sqrt{b^2\omega^2+(k-m\omega^2)^2}}\cos\left(\omega t-\tan^{-1}\frac{b\omega}{k-m\omega^2}\right).$$

If we denote by y the vertical displacement of C above S (that is to say, when SC is measured upwards y is positive), then we can show in the same way as before that

$$y=\frac{m\omega^2e}{\sqrt{b^2\omega^2+(k-m\omega^2)^2}}\sin\left(\omega t-\tan^{-1}\frac{b\omega}{k-m\omega^2}\right).$$

Combining x and y, we get the position of C at the end of a revolving vector whose length is $\frac{m\omega^2e}{\sqrt{b^2\omega^2+(k-m\omega^2)^2}}$, and whose phase position is a certain angle ϕ behind the vector CG (Fig. 72), the value of ϕ being

$$\tan^{-1}\frac{b\omega}{k-m\omega^2}.$$

If $b=0$, we get, as on page 122, the deflection

$$D_f=\frac{m\omega^2e}{k-m\omega^2}.$$

The value of ϕ is then zero, so that S lies on the line CG, and all that we have said on page 122 as to positive deflection below the speed of resonance and negative deflection above the speed of resonance holds.

Now give b a finite value and the angle ϕ becomes finite, so that S is no longer in line with CG. We must be very careful in construing our signs $+$ and $-$ in connection with the vectors. It must be remembered that S is the centre of our vector diagram and we count ωt from the time when CG is in the position shown in Fig. 72. For any given values of the constants m, ω, b and k we have a definite

value of the angle ϕ, which is measured as shown in Fig. 72. In this figure t is zero. As t increases the whole figure revolves about S, the angle ϕ remaining constant and SC remaining a vector of constant length.

At the critical speed $k = m\omega^2$, so that ϕ becomes a right angle, and the horizontal deflection becomes

$$x = \frac{m\omega^2 e}{b\omega} \cos\left(\omega t - \frac{\pi}{2}\right) = -\frac{m\omega e}{b} \sin \omega t,$$

and the vertical deflection becomes

$$y = -\frac{m\omega e}{b} \cos \omega t,$$

so that our vector diagram for $t = 0$, is given in Fig. 73.

That is to say, that the deflection lags 90° behind the vector CG, and in amount it is proportional to the mass and to the speed and to the eccentricity e, and inversely proportional to the damping constant b.

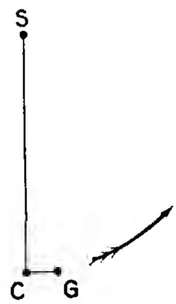


Fig. 73.

In order to realize how narrow the resonance zone is when we are dealing with high speed turbo rotors, it is of interest to insert actual constants for m, b and k as found in practice. We may measure the force in grams-weight, and the mass in units consisting of 981 grams; so that for a rotor weighing 2700 kilograms, we have $m = 2750$. For a normal speed of 3000 r.p.m., we have $w = 314$ radians per second. In order to avoid resonance the stiffness of the shaft may be such as to make $k = 1{\cdot}48 \times 10^8$ grams weight per centimetre deflection. This will give a critical speed of 232 radians per sec. for $mw^2 = 2750 \times 232 \times 232 = 1{\cdot}48 \times 10^8$.

The amount of eccentricity that one might have in practice is, say, that due to 100 grams at a distance of 38 cms. from the centre This will make

$$e = \frac{100}{2{\cdot}7 \times 10^6} \times 38 = 1{\cdot}4 \times 10^{-3} \text{ cms.}$$

With this amount of eccentricity a damping constant of 13000 will limit the deflection to 0·069 cm. We will take therefore, the following constants:

$$m = 2750,$$
$$k = 1{\cdot}48 \times 10^8,$$
$$b = 13000,$$
$$e = 1{\cdot}4 \times 10^{-3}.$$

Filling these values in the formulae on page 124, we may find the amount and phase of the deflection for the different values of ω,

These may be plotted as shown in Fig. 74, and give us the deflection-graph for the above constants. The value of k and $m\omega^2$ are so great as compared with b, and the value of $(k-m\omega^2)$ changes so rapidly near the critical speed for small changes in ω, that the marked resonance zone lies between $\omega=230$ and $\omega=234$. The corresponding speeds in revs. per minute are 2195 and 2235. That is to say, a change of speed of 2 per cent. is sufficient to carry

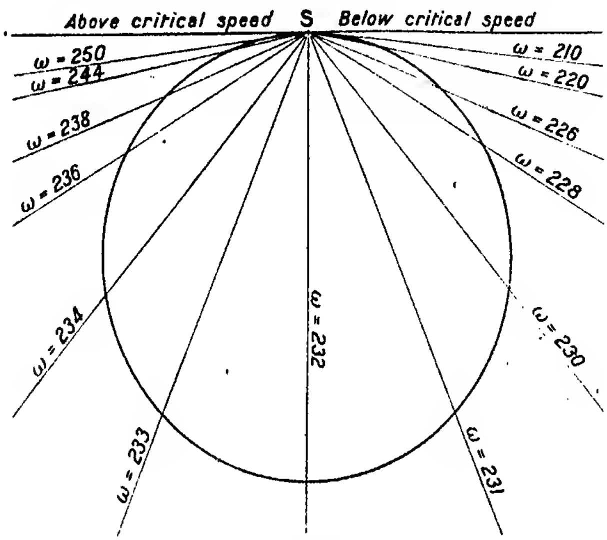


FIG. 74.—Deflection graph of turbo rotor. Scale; 1 cm. in diagram represents 0·01 cm. of deflection.

the rotor through the resonant zone. If the damping constant is greater the resonant zone is wider, and the amplitude of the vibration is less for a given eccentricity.

When the resonant zone is narrow the deflection-graph is indistinguishable from a circle,* as seen from Fig. 74.

* The proof of this is as follows: Let ω be very nearly constant; then we have the deflection represented by a radius vector whose length is

$$r=\frac{a}{\sqrt{R^2+X^2}},$$

and whose phase-angle is

$$\phi=\tan^{-1}\frac{R}{X},$$

where a and R may be taken as constants and X is the variable.

As X is equal to $(K-m\omega^2)$ where k and m are great, it may pass from a great positive value to a great negative value for a comparatively small change in the value of ω.

In Fig. 75 the line OQ may represent the constant R to scale, OS being taken as unity

On lower speed machines the eccentricity may be greater without causing very excessive vibration, and as $(k-m\omega^2)$ does not change so quickly for small percentage changes in ω it is easier to adjust the speed to the critical value and obtain the marking at right angles to the heavy point. With high speed machines, however, it is difficult to do this with certainty, because a change of speed of a few parts in a thousand takes us from one side of the graph to the other. Where it can be done, it is best to balance the machine at its critical speed, because the indications of the pencil lines are then most pronounced; and if we secure a fairly good balance at this speed, we shall find on running at normal speed that the machine is almost free from vibration. For the reasons given above, however, we must expect to have very erratic markings of the pencil when running in the resonant zone; but if we know something of the deflection-graph we shall not be dismayed by them.

Practical hints on balancing.

In setting out to balance turbo rotors the following is a good course of procedure. Make sure that the surfaces of the shaft at both ends of the rotor just outside the journals (see Fig. 66) are concentric with the journals. Prepare these surfaces to receive the pencil mark. This is best done by polishing the shaft with a piece of emery cloth, the direction of scratching of the emery being made with lines parallel to the axis. This makes the pencil line very much more visible. It will be found that a steel shaft takes the pencil more readily if it has on it a very thin coating of machine oil. It is sufficient to put oil on with a rag and then wipe all off that can be wiped with a rag that is almost clean. The kind of pencil that marks the best on a shaft is the ordinary blue or red crayon sold by the stationers, which has a rather soapy core. In rubbing off old markings use an oily rag, so as not to spoil the cross emery scratchings.

Where possible, arrangements should be made to **run the rotor in both directions.** The balancing can then be done very much more

Then $OT = \frac{1}{R}$. If we draw a circle on the diameter OT it forms the inverse of the line UV, O being the point of inversion.

In Fig. 75, we have $\phi = \tan^{-1}\frac{R}{X}$,

while X is varied and R kept constant.

Now $\sin\phi = \frac{R}{\sqrt{R^2+X^2}}$,

and as we can write $r = \frac{a}{R} \times \frac{R}{\sqrt{R^2+X^2}}$,

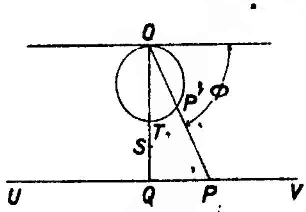


Fig. 75.

we have $r = \text{constant} \times \sin\phi$, which is the polar equation of a circle.

readily. In some cases, however, as where the turbo-machine is driven by a steam turbine, it is only possible to run in one direction.

A tachometer should be attached to the rotor for the purpose of accurately indicating the speed at any instant; or the stroboscopic method of speed measurement described on page 77 may be used.

Assuming that it is possible to run in both directions, *run first in a clock-wise direction, gradually increasing the speed until some vibration of the bearings is observed. Then mark both ends of the shaft lightly, at the same time noting the speed. If the speed attained when* the out-of-balance is observed is only a few hundred revolutions per minute, we may assume that it is a long way below the critical speed and the marking at each end of the rotor probably shows the heavy side at that end of the rotor. However, the indication in this respect is rather indefinite. There may be other factors controlling it. Leaving the marks as they are, run the rotor in a counter-clockwise direction up to exactly the same speed as before and again mark the shaft, the pencil being held, say, ⅛th inch nearer the rotor than before. Now shut down the machine. If the marking at one end has been caused by the shaft coming out on the heavy side at that end, then the clockwise mark and the counter-clockwise mark will almost correspond and indicate the side on which the rotor is heaviest. If they do not correspond, take the point midway between the centre of each line as the heaviest point. In general, the markings at one end of the shaft will be different from the markings at the other end. Now fix a balance weight at each end to counter-balance the heavy side and run the rotor again. It is a good plan in the first instance to put a rather heavy balance weight at each end, and to run the rotor up to the same speed as before, both in a clockwise and in a counter-clockwise direction and make two new marks. If the balance weights which have been attached are too heavy, the new marks will be on the opposite side of the shaft. This proves that we are on the right lines. Now reduce the balance weights to an amount which appear from the last markings to be about right. It will now be found possible to run the rotor up to a higher speed before very bad vibration occurs. If the speed is still below the critical speed proceed exactly as before, adding a little more balance weight or taking a little off according to the indications obtained. We can proceed in this way until we almost reach the critical speed. It will then be found that the markings in the clockwise direction and in the counter-clockwise direction become gradually further and further apart. The place to put the weight is midway between the markings if the speeds in both directions are identical. As we have seen on page 126, when we are near the critical speed very small differences in speed will give very great changes in the position of the mark; so that it is well to be guided by

our previous knowledge of the heavy point, and not trust too much to the bisection of the distance between the markings made in opposite rotations. When the critical speed has been reached, the markings will occur on opposite sides of the shaft. Now it must be remembered that the place to add the weight is 90° behind the marking. The critical speed is the best speed at which to run the turbo when balancing it, because the indications of want of balance are most pronounced. *It is hardly possible to balance a machine so well that vibration is not noticeable at the critical speed, but if we succeed in getting down the vibration to a small amount in the resonance zone, it will be found that we can then run up to full speed and the vibration will then be very much diminished.*

Where a machine is designed to run below its critical speed it may not be safe to run it at its critical speed, and in this case the balancing must be done at the highest speed that is safe, the position at which the balance weight is attached being indicated as before.

If it is not possible to run the rotor in both directions, some judgment must be used in fixing upon the position at which to attach the balance weight. As a rule in turbo-machines, the zone of resonance is very narrow, so that the markings are for the most part on the heavy side below resonance, and in the light side above resonance. The same principles are applied as in the foregoing. In actual practice the procedure is not quite as simple as that indicated above, because the movement of the rotor is more complex than that prescribed by the simple theory. This is especially the case when the rotor is direct connected to a steam turbine or another machine. For this reason it is well to loosen all couplings that may tend to interfere with the rotor's own movements. In case the heavy side of the rotor is different at each end, a curious wobbling motion is given to the rotor, which interferes with the simplicity of the markings as outlined above. Working on the lines we have laid down, however, it is possible to get a general indication of where to put the weight at one end A, so as to improve the running at that end. Then moving to the other end B we shall find that the disturbances created by A are less than before, so that we can get a fair indication of where to put the weight on the B end. Fixing this as far as possible from the indications, we then go back to the A end where the indications are now more precise, and after getting a better balance there we proceed to the end B again, and so on, until a good balance is obtained at both ends.

In fixing balance weights during these tests very great care must be taken to secure the weight in a way that is very positive, so that there is no fear of its flying out during the run. When the amount and position of the balance weights have been definitely ascertained the weight should be prepared in copper or other suitable metal and

*fixed in a thoroughly permanent manner. When standing near a turbo-machine (especially if it is being run up for the first time) always stand out of the "line of fire," unless there is some reason for standing in the more dangerous place.**

Shifting balance. Sometimes it is found when balancing a turbo-rotor that a fairly positive indication is obtained as to the position in which the balance weight should be put, but before the right amount of the weight has been adjusted a clear indication will appear that a big weight is required in an entirely new position. Concentrating now on the new position, an attempt is made to ascertain the amount of the weight required, and then suddenly the markings indicate an entirely new position again, and so on. This effect sometimes occurs on rotors which are built up of laminations threaded on a shaft and very firmly bolted together. Under these conditions the shaft sometimes bends when running at or near the critical speed, and the friction between the plates is sufficient to preserve the bend, so that the balance is upset. With a new weight in position the shaft may again bend in another direction, so giving a new indication of want of balance. It is of course impossible to obtain a good balance on a machine behaving in this way. We must either be content with the best balance obtainable or have the rotor rebuilt on a new plan.

In the case of **moderate speed** machines in which we are obtaining a running balance, the same rules are of course applicable, except that in general it will not be possible to run the machine up to the critical speed and the markings of the pencil indicate very closely the heavy side. Sometimes, however, the markings are complicated by the wobbling action of which we have spoken, in which case we must be prepared to put weights on both ends of the rotor, proceeding alternately from end A to end B, as indicated above.

PULLING OVER.

The types of machines which are most liable to pull over are (1) Slow-speed alternators having a large number of poles and an air gap which is short as compared with the diameter of the machine, and (2) large diameter induction motors which have a short air gap.

After an alternator has been erected, the field-magnet is carefully centred, the air gap, top and bottom, at both sides and at both ends of the machine being measured by means of suitable wedges. One should not be content with centring the field magnet in one position after finding the centre true; it should be barred round through 90°, the centre checked again and then barred round through another 90°

* The author knew one man who lost his life by not attending to this rule, and one man who saved his life by attending to it.

and the centre checked. Sometimes the rotor is slightly eccentric, especially when it has been pressed on the shaft on site as is sometimes the case on big engine-type machines. It is not a bad plan on these big machines to make the air gap at the top about five thousandths of an inch less than at the bottom. The unbalanced pull then supports a fraction of the weight of the rotor. This is better than having the air gap at the bottom less than at the top, for under these circumstances the unbalanced magnetic pull would be added to the weight of the rotor. Where the machine is separately excited it will be possible to excite the field-magnet while it is stationary. If we wish to check the stiffness of the shaft and the frame in this respect we may deliberately make a displacement of about $\frac{1}{32}''$ and try whether a pull-over occurs when the no-load field-current is switched on. If a pull-over occurs with a $\frac{1}{32}''$ displacement, the manufacturers should be informed of the fact because all machines are supposed to have their shaft and frame sufficiently stiff to withstand this accidental displacement without pulling over. Although a machine may run quite well when perfectly centred, there will always be a danger of a small accidental displacement and a pull-over occurring when the machine is in operation. A pull-over may be due either to the shaft not having sufficient stiffness or the frame of the machine not having sufficient stiffness. In both cases the tendency to pull over can be reduced by increasing the air gap. Before this is done, however, you must ascertain whether there is any margin in the heating of the field-coils. Whether there is a chance of substantially improving the conditions by increasing the air gap can be judged by the following formula. In cases where the iron of the magnetic circuit is not saturated the difference of pull in kilograms on the two sides of a machine

$$=4{\cdot}05\times10^{-8}\times B^2\times\text{No. of poles}\times\text{sq. cm. pole area}\times\frac{a}{g},$$

where g is the length of the air gap and a is the displacement of the centre of the rotor from the true central position, and B is the flux-density in the gap. It will be seen that in this case the magnetic pull is inversely proportional to the length of the gap, so that if the gap can be increased by 50 per cent. the pull can be reduced * by 33 per cent. This is in machines in which the magnetic circuit is not saturated. In some cases, however, there is considerable saturation in the magnetic circuit and the unbalanced magnetic pull may be diminished to less than one half of the amount given by the above formula owing to saturation. If, notwithstanding saturation, the unbalanced magnetic pull is in fact sufficient to bring about a pull-over, the increasing of the gap will as a rule have very little effect, and one

* For method of calculating the effect of saturation on the unbalanced magnetic pole, see *Specification and Design of Dynamo Electric Machinery*, p. 358.

can hardly hope to effect a cure in that way unless there is so much margin in the heating of the field that a very big change in the length of the gap can be made.

If it is impossible to reduce the unbalanced pull and the trouble arises from the springing of the frame, it may be possible to stiffen the frame by a suitable structure attached to it. This is a matter for the manufacturer.

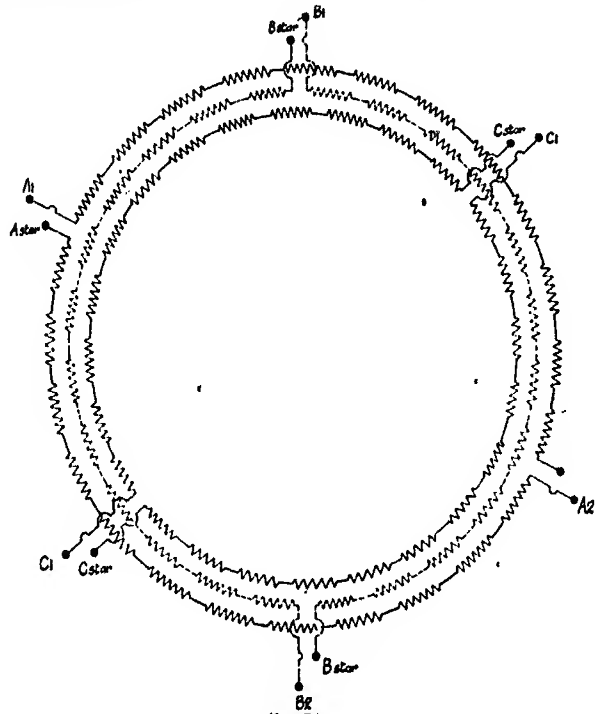


FIG. 76.

Where an induction motor has a wound rotor and full voltage is thrown on the stator at starting it may be that a pull-over occurs under these conditions. The rotor should be very carefully centred with the rotor turned round to various positions and note made of any eccentricity in the rotor that may be found in trying the air gap in these different positions. If there is any eccentricity the rotor should be ground true. A pull-over on an induction motor, if it occurs with the rotor in an almost central position is invariably due to the air gap being too short, having regard to the stiffness of the shaft and the stiffness of the frame. The right remedy is for the manufacturer to stiffen these parts. Sometimes, however, matters

can be improved by putting two halves of the rotor winding in parallel. The voltage for which a rotor is wound is not a matter of great importance in the operation of the machine. Moreover, in many cases, the slip rings of the rotor will stand double current for the short time required for starting up. If, therefore, it is possible to break up each phase of the rotor into two parts and connect them in parallel as shown diagramatically in Fig. 76, so that each of the parallel circuits of one phase are on diametrically opposite sides of the rotor, this should be done. The tapping points of the different phases should preferably be spaced at 60° apart. The putting of two diametrically opposite parts of a winding in parallel has the effect of equalising the flux on the two sides of the machine; because it is impossible for a great difference in the flux to occur without the flowing of heavy circulating currents which have a magnetising effect on the side where the air gap is long, and a demagnetising effect on the side where the gap is short. The putting of the rotor circuits in parallel is not quite as powerful in its action in this respect as the putting halves of the stator winding is parallel, but if a stator has not been designed for this arrangement the change must be made on the rotor and not on the stator.

Machines with **squirrel cage windings** already have this parallel connection in the rotor circuit, and are therefore very much less liable to pull over than wound rotors. Where, however, a rotor becomes very much displaced, so that the air gap at one side becomes reduced to only a small fraction of the gap at the other side, the unbalanced magnetic pull can be sufficiently great, even on a squirrel-cage rotor, to bring about a pull-over.

Direct current generators. D. C. generators are not much troubled with the defect considered under this heading, because the air gap is usually fairly great and the machine is seldom excited when it is not running. If it is running the cross-connections on a lap-wound machine throw diametrically opposite parts of the winding in parallel and sufficiently equalise the flux to minimise the unbalanced magnetic pull even in the case of quite large displacements of the armature.

EDDY-CURRENTS IN JOURNALS AND BEARINGS.

In order to successfully investigate and cure trouble from eddy-currents in journals and bearings it is necessary to understand the several causes that give rise to these currents. The causes fall into two main classes: (1) Homopolar effects, (2) Transformer effects.

(1) Homopolar E.M.F. in bearings.

Whenever a revolving shaft is magnetised so that the lines of force emanating from the journal regarded as a magnetic pole come-

out through the metal of the bearings, we have all the essential elements of a homopolar generator. If we look upon the magnetic pole as revolving, then we may say that an E.M.F. is generated in the metal of the bearings because it is being cut by the magnetic lines from the journal. Or, if we prefer it, we may say that the magnetic pole is stationary, being fixed to the coils or other source of magnetomotive force, and in that case we may say that an E.M.F. is generated in the journals because they are moving in a magnetic field. Whichever way we take it there is an E.M.F. along the paths indicated by the chain-dotted lines in Fig. 77. This E.M.F., often only a fraction of

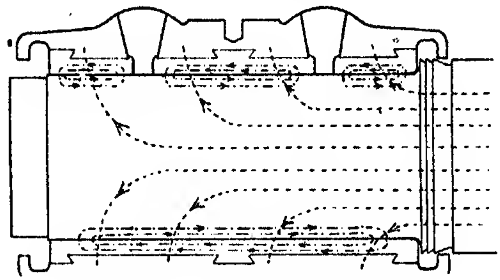


FIG. 77.

a volt, may be sufficient to make quite large currents flow when the conditions of the bearings are such as to bring the surface of the journal in contact with the surface of the bearing. If the bearing and the oiling arrangements start under good conditions, the oil forms an insulating layer; and even though the homopolar E.M.F. is considerable, the film of oil may be sufficient to prevent any current flowing. It is very common for shafts to be magnetised and for no trouble to be apparent. On large turbo-generators where the total flux coming from a magnetised shaft may be considerable, and where the speed is high, the danger from the homopolar effect is greater; and trouble sometimes arises from this cause when a machine is first started up and the bearings are not so good as to preserve a perfect layer of oil insulation. The effect shows itself in a pitting of the surface of the journal. This pitting appears to be due to the breaking of the current by the film of oil from time to time. The pitting brings about a roughness of the journal, which prevents the oil from making as good an insulating layer as it otherwise would do. In cases where pitting of the journals is noticed we should ascertain whether the journal is magnetised. Sometimes it is permanently magnetised, so that a compass needle will give an indication when the machine is stationary, and sometimes it is only magnetised when the field-magnet is excited. Again, it may be that the shaft is only magnetised when

the machine is on load. The investigator should determine by exploring with a compass needle under which of these circumstances the magnetisation occurs. There may be a weak permanent magnetisation of the shaft which is strengthened when the field-magnet is excited or when the machine is on load. The residual magnetism may reside partly in the shaft and partly in the bed-plate. Cast-iron has a fairly high coercive force, and if once strongly magnetised a big bed-plate can keep up a heavy magnetic flux through the journal and shaft back to the frame of the machine. The investigator must hunt for the magneto-motive force which originally produced this magnetisation.

Magnetisation of the shaft by the field-magnet.

When the magnetisation is strengthened by the field being excited, but not strengthened on load, the following may be some of the causes:

(1) Single bobbin field-coil. On generators which have a field-magnet like that in Fig. 78 excited by a single field-bobbin, the

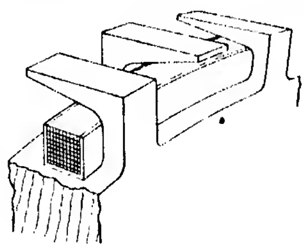


FIG. 78.

whole of the shaft will be found to be highly magnetised when the field current is passing. Some inductor machines have a single stationary field-coil between two parts of the stator. This field-coil may produce very heavy magnetisation of the shaft.

(2) All field-coils of same polarity. Some alternators and synchronous motors are designed to have all field-coils of the same polarity, these being put on alternate poles and the intermediate poles forming a return circuit without any magnetising coils.

Machines of this kind invariably magnetise the shaft. If there are 8000 ampere-turns upon each field-coil, the 8000 ampere-turns exert a magneto-motive force around the circuit which consists of the spider of the alternator, the shaft, the pedestal, the bed-plate, the frame and the air gap.

In cases (1) and (2) the magnetisation of the shaft can be cured by providing a stationary coil encircling the shaft and carrying a current which will exert a magneto-motive force opposite to the magnetising force of the field-coils and sufficient to reduce the magnetisation to zero. In general one coil will be required for each journal.

(3) Dissymmetry in winding. In two-pole turbo-generators it is possible for the shaft to be magnetised through some dissymmetry either in the field-winding or in the mounting of the field-magnet. The magneto-motive forces on some turbo-generators consist of so very many thousand ampere-turns that what is comparatively a small dissymmetry in ampere-turns, taken as a percentage of the whole, may give rise to a rather powerful magnetisation of the shaft. If, for instance, one pole of a turbo-alternator has 40,000 ampere-turns on it, the short-circuiting of only 5 per cent. of the coils will lead to a dissymmetry of 2002 ampere-turns, which is quite sufficient to magnetise the shaft very heavily. The same thing may arise on 4-pole and 6-pole machines, but the greater number of poles the greater the percentage of coils that must be short-circuited in order to produce an appreciable effect.

Where the point of dissymmetry is something which belongs to one pole, as where part of the magnetising coil of a north pole is short-circuited, the shaft will be magnetised with a constant polarity. There are other dissymmetries, however, which may give an alternating polarity to the shaft. If, for instance, the air gap in a two-pole turbo-alternator is made slightly greater at the bottom than at the top there will exist a difference of magnetic potential between the frame and the point midway between the two poles on the field-magnet. When the north pole is at the top some flux will flow from this north pole to the frame along the bed-plate to the bearings and back through the shaft. When the south pole comes to the top the direction of the flux will be reversed. This reversal of the flux itself produces an eddy-current in the shaft, whose effect is considered on page 139, but when the machine is stationary and the field-magnet is excited we have a powerfully magnetised shaft which for the time being is of constant polarity. Sometimes the shaft and bed-plate have a very great residual magnetism which has been caused by field-current having been passed through a field-magnet while it was out of centre. It may be during the course of erection, before the field-magnet was properly centred. This residual magnetism, if it has not been removed, may give rise to homopolar effect.

(4) Magnetisation of shaft by load current. In D.C. generators generating very large currents sufficient care is not always taken, in bringing out leads from a machine, to avoid the magnetisation of the frame. Whenever cables carrying very heavy currents are connected to dynamo-electric machines, the positive lead and the negative lead should never be separated by any magnetisable member so as to interfere with the symmetry of the magnetisation of the frame. Fig. 79 shows an arrangement of the positive and negative leads connected to a D.C. generator which at first sight looks innocent

enough, but if each of these leads carried 2000 amperes, we should have a magneto-motive force of 2000 ampere-turns thrown upon the magnetic circuit, consisting of the shaft, bed-plate, and pedestal. This magneto-motive force might be quite sufficient to cause trouble with the journals.

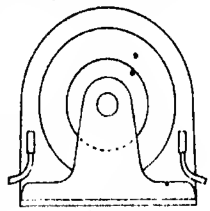


FIG. 79.

It is quite a common practice to connect all the series coils of a D.C. generator in series and then to connect the last coil to the terminal. Where this is done the load current of the machine makes one complete turn around the shaft and may exert a very considerable magneto-motive force on the shaft-pedestal-frame magnetic circuit. All machines generating a very heavy current should have their series coils divided into two groups, one of which is magnetised by a current going one way round the shaft and the other by a current going the other way round. In cases where it is known that the commutating-pole current will be substantially the same as the current in the series coils, it may be sufficient to pass the current one way round the shaft when going through all the series coils and the other way round the shaft when going through the commutating pole coils. Whenever a D.C. machine exhibits evidence of having a magnetised shaft, a close inspection should be made of all the main connections and series coils to see if there is any threading of a positive current through the shaft-pedestal-frame magnetic circuit which is not counter-balanced by the threading of a negative current. Sometimes a machine which generates only a comparatively small current on normal load may exhibit very heavy remanent magnetism in the shaft-pedestal-frame magnetic circuit, this remanent magnetism having been produced by an exceedingly heavy current which flowed for only an instant, when the machine was short-circuited at some time in its history. Sometimes the pitting observed in bearings is only produced at the instant of very heavy short-circuits, which occur from time to time on a traction generator. These heavy currents on short-circuit may have very destructive effects in ball bearings.

(2) Transformer effects.

There are many ways in which an electro-motive force may be set up in the journals or bearings of a generator by what are here called "transformer effects" in default of any other name of sufficiently wide significance. The elements which enter into the phenomena falling under this heading are: (*a*) An electric circuit consisting of the shaft, two pedestals and a bed-plate, as in Fig. 80; (*b*) a magnetic circuit threaded through circuit (*a*); and (*c*) a changing magneto-

motive force which causes a varying flux in the magnetic circuit (*b*), thus giving rise to an E.M.F. in circuit (*a*). There are very many circumstances which can supply these three elements. It will only be possible here to point out some of them.

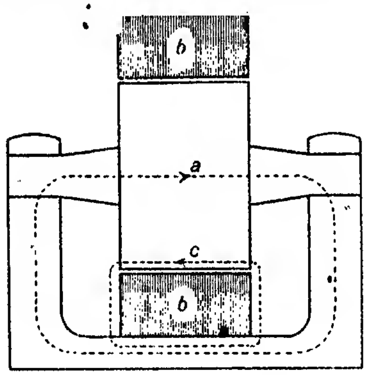


FIG. 80.

(5) A fairly well known case is the case of the split in the stator iron of a revolving field-generator, the action of which is illustrated in Fig. 81 and Fig. 82. When the 4-pole field takes up the position shown in Fig. 81, the centres of the north poles being opposite the split in the stator iron, flux from the poles divides in a symmetrical manner,

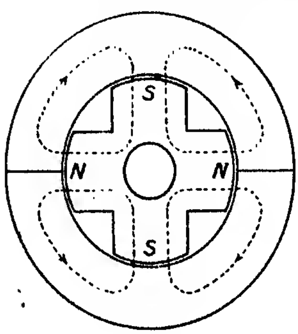


FIG. 81.

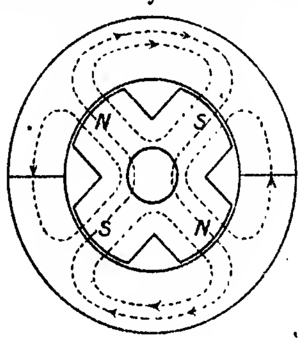


FIG. 82.

and it cannot be said that there is any flux threading through circuit (*a*). When, however, the field-magnet gets into the position shown in Fig. 82, the reluctance of the split in the stator iron causes more of the flux between the north and south poles in the lower part of the machine to return by the lower half of the stator than returns by the parts of the stator containing the split. We therefore have momentarily a change of flux occurring in circuit (*a*). The per-

centage of flux causing the dissymmetry may be extremely small expressed as a percentage of the whole flux, but on a big turbo-generator having many mega-lines per pole the unsymmetrical flux is sufficient to generate quite enough E.M.F. in the circuit (*a*) to cause bad pitting of the journals.

(6) Unsymmetrical position of field-magnet. The same kind of effect as that described in the last paragraph can be produced through having a field-magnet mounted in an unsymmetrical position, especially when the ampere-turns on the stator core are fairly great. Fig. 83 shows a field-magnet mounted so that the air gap at the bottom is less than the air gap at the top. This dissymmetry brings about two sources of E.M.F. in the bearings. In the first place there is a difference of magnetic potential between the centre of the shaft and the external frame. When the field-magnet is mounted centrally both should be at zero magnetic potential; but if the 2-pole field-magnet shown in Fig. 83 has its north pole moved nearer to the stator iron than the south pole, the magnetic potential of the whole frame will be raised above the potential of the centre of the shaft and flux will flow through the bed-plate, along the pedestal and back by the shaft. When the field-magnet makes a half revolution the south pole comes nearer to the stator iron than the north pole, so that the flux will now flow from the shaft in the opposite direction through the pedestal and back by the bed-plate. There will be a tendency for the flux to alternate as the field-magnet revolves. The metal parts through which this flux can flow are solid, and an alternating flux cannot be produced in them without setting up heavy eddy-currents, which oppose the flow so that the effect of the unsymmetrical mounting is to create in the shaft and bed-plate eddy-currents whose magneto-motive force is almost equal and opposite to the magneto-motive force set up by the unsymmetrical mounting. In addition to this effect there is a tendency, when the axis of the north and south poles becomes horizontal, for the total flux in the lower half of the frame to be greater than the total flux in the top half, and as the south to north pole axis alternates in its position, this unsymmetrical arrangement of the flux sets up a transformer E.M.F. in the (*a*) circuit. This second effect is produced whatever the number of poles, but is more marked when the poles are few than when it is great.

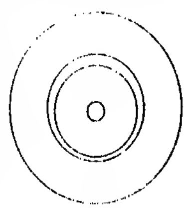


FIG. 83.

(7) Momentary heavy current. Where the leads to a generator are so taken away that they embrace the (*b*) magnetic circuit, a very heavy current, such as may occur when the generator is short-circuited, will as it rises induce an E.M.F. in the (*a*) electric circuit. This sometimes happens in the case of a rotary convertor feeding a

traction load. A short-circuit may occur on the traction system, causing a great rush of current from the rotary amounting to many thousands of amperes. This creates a changing magnetic field, which embraces the (a) circuit and causes a current to flow from the journals to the bearings. In the case of rotaries on ball bearings on a certain traction system this effect so repeatedly ruined the ball-race that other bearings were substituted. The right remedy is to insulate the pedestal of the bearings so that the current cannot flow (see page 145).

(8) Hemitropic windings. If we have a single-phase machine in which the coils are hemitropic * any current in the armature coil sets up a magneto-motive force which creates a difference of magnetic potential between the centre of the shaft and the outside frame, and an action is set up similar to that considered in the last paragraph.

(9) Break-joints in iron of revolving armature. Sometimes the break-joints in armature iron produce very complex effects that are difficult to fathom without a long investigation. When armature iron is built up in sectors it is not uncommon to have a gap of $\frac{1}{32}''$ between two sectors that lie in the same layer, and although the alternate layers are arranged so as to break joint the total reluctance of the joint is much higher than the reluctance of other parts of the armature core. As long as the saturation of the iron is small the reluctance of the joint is negligible, because the half section of iron in the joint is easily able to carry the total flux. When, however, the flux is increased up to the saturation point, the half section of iron in the joint becomes super-saturated and the reluctance of the joint is by no means negligible. The existence of a difference of magnetic potential between the two sides of a joint in an armature can be demonstrated by means of a piece of soft iron bent into the form of a horse-shoe as shown in Fig. 84. It is often possible to get at the inside of the punchings of an armature through the openings in the spider. If in one of these openings we can find a place where a break-joint appears, we may place the little horse-shoe with its flat ends against the armature iron and arrange it so as to bridge the joint. We now pass current through the field-magnet. It will be found that the horse-shoe will not stick on to the armature iron for low excitations of the field-magnet, but if the excitation is increased up to a point sufficient to create a flux of 10,000 or 11,000 lines per square centimetre in the armature iron, the horse-shoe will be attracted and stick to the armature iron. It is convenient when trying this experiment to attach a string to the centre of the horse-

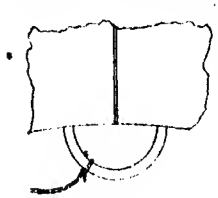


Fig. 84.

* See *Specification and Design of Dynamo Electric Machinery*, p. 88

shoe to prevent it from falling into the machine. If the flux density is increased to $B=12{,}000$ or 13,000, the pull on the horse-shoe may become quite considerable. The amount of the pull depends upon the width of the air gap between punchings lying in the same layer.

The magneto-motive force required to drive the flux across the joint may in some cases be so considerable as to drive the flux into

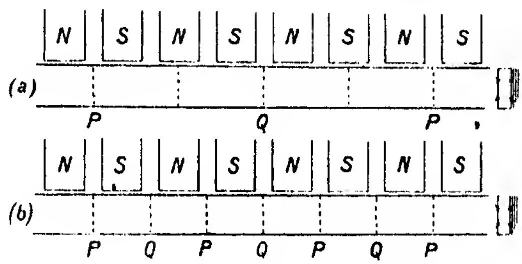


FIG. 86.—Showing P joints and Q joints in action at the same time.

the cast steel end-plates of the armature which otherwise would not carry so much flux. If now the number of break-joints bears a certain relation to the number of poles, very mysterious E.M.F.'s may be set up in the (a) circuit. The relation between the number of joints and the number of pairs of poles which may cause trouble in this way will be understood by reference to Figs. 86 and 87, in which

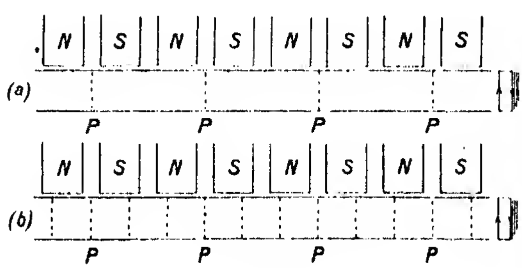


FIG. 87. Showing P joints only in action.

the joints in the punchings are indicated by dotted lines. Those joints which have a north on the left side and a south on the right are marked P and those which have a south on the left side and a north on the right are marked Q. Those which are not between poles are not marked. When a P joint travels from right to left there will be an eddy-current in the end-plate opposing the growth of flux in it, that is to say, it will be a current flowing up the front side of

the end-plate and down the inside as shown in the side projection. Opposite the Q joints there will be an eddy-current flowing in the opposite direction. If at any instant there are as many P joints as Q joints, the sum of all the eddy-currents in the end-plates will not exert any resultant magneto-motive force around the whole end-plate, regarded as constituting the magnetic-circuit (b). If, however, there are at any instant only the P joints in action there will be a resultant magneto-motive force around the whole (b) magnetic-circuit, and there will be a transformer action between this eddy-current and the (a) circuit. Let the highest common factor of the number of poles and the number of breakjoints be denoted by F. Then if the quotient obtained by dividing the number of poles by F is odd, we will find that the P joints are always balanced by the Q joints.* If the quotient is even the P joint and Q joint come into operation at different instants, and therefore do not balance. For instance, if we have 12 poles and 8 breakjoints, $F=4$; $12 \div 4 = 3$, which is odd. This arrangement gives no resultant magnetisation around the (b) circuit. If we have 8 poles and 12 breakjoints, $F=4$; $8 \div 4 = 2$, which is even. This arrangement is illustrated in Fig. 87 (b), from which it will be seen that the P joints only are in action on the position shown. When the armature has moved through one-third of a pole-pitch, only the Q joints will be in action. We shall, therefore, have an alternating effect set up in the (a) circuit, the frequency of which is three times the frequency of the machine. A case of this kind arose in the author's experience on an 8-pole D.C. generator, which had 12 breakjoints in the armature iron, that is to say, 3 joints per pair of poles. When the machine was fully excited and run at no-load, a heavy current flowed from the shaft to the bearings, and *vice versa*, which on investigation proved to be an alternating current having three times the frequency of the machine. The current entirely disappeared when the saturation was low. It was very weak at low stages of saturation, and only became serious when the flux density in the core reached the value of 12,000 C.G.S. lines per square centimetre. It was found possible to make a little horse-shoe of soft iron stick on the core as described on p. 140, when the field-magnet was fully excited. This particular armature was built with heavy cast steel end-plates. Apart from eddy-currents in the end-plates, when the conditions illustrated in Fig. 87 hold, there will be an alternating flux in the (b) circuit generated in the manner described with reference to Figs. 81 and 82.

* Another way of stating the matter is as follows. If the number of poles divided by the number of joints is equal to one of the following numbers, 1, 1½, 2½, 3, 3½, 4½, 5, then the P joints and Q joints will balance. This series of numbers contains all the odd numbers and all the odd and even numbers plus one half.

Method of investigation.

The plan of procedure when we wish to find out the cause of an eddy-current in the shaft is in the first place to find out exactly the conditions under which it occurs and secondly to find out the exact nature of the current that is flowing. In investigating the circumstances under which it occurs, we have to be on our guard against multiplicity of effects. It is quite common for a shaft to be magnetised and to have a slight homopolar effect which is doing no harm and which would pass unnoticed if it were not for another effect which only occurs under special conditions. When we begin to hunt for the cause of the eddy-current, say by running the machine at no-load and connecting a milli-voltmeter from the shaft to the bearing, the innocent homopolar effect gives us an indication of a continuous voltage which we may mistake for the cause of the trouble. While the low reading voltmeter is a more convenient instrument to work with than an ammeter, its indications in investigations of this kind must be taken with all due caution. The resistance of the film of oil between the journal and the bearing is generally an unknown quantity, and therefore a reading of the voltage between the journal and the bearing is not a very certain indication of the extent of the effect that we are investigating. It is, however, convenient to begin with a low-reading voltmeter and to run the machine unexcited and see if there is any voltage difference between the journal and the bearing. We shall generally find a few milli-volts due to accidental magnetisation of the shaft. Now excite the field-magnet fully and see if the reading of the voltmeter is increased. If we have a large increase of D.C. voltage we have evidence of the existence of one of the effects described on pp. 134 and 136. If there is no increase in the D.C. voltage, take a low reading A.C. voltmeter, and try again with the machine both excited and unexcited. If there is an A.C. voltage it is evidence of one of the effects (5), (6), (7) or (8) described on pp. 138 and 140. Now make arrangements for connecting an ammeter between the journal and the bearing. This can be done by cleaning out the centre-point at the end of the shaft so that it is perfectly free from oil, and arranging a clean copper gauze brush in the form of a cone so that it can be forced into the centre-point and so make a very low resistance contact between the shaft and the cable which is carried to the ammeter. The other cable from the ammeter should be screwed down under one of the bearing bolts. Both a D.C. ammeter and an A.C. ammeter should be tried, the impedance of the ammeter circuits being kept as low as possible. This will tell us whether the current is D.C. or A.C. and give us some rough idea of its amount. We can never, of course, be sure what fraction of current goes through the ammeter and what through the bearing. Sometimes the current will

amount to many hundreds of amperes. The ammeters will give us a very good idea of the circumstances under which the current flows, and the state of the excitation and the condition of saturation and load at which it becomes increased. We shall sometimes find that there is a considerable D.C. flowing all the time even when the machine is unexcited, but that it is only under certain conditions that a large alternating current is superimposed upon this. If the data thus obtained do not make the cause of the phenomenon sufficiently clear, the next step is to find out the frequency of the alternating current. This can be done by means of an oscillograph if there is one available. If no oscillograph is available we can make a thorough investigation of the frequency and phase of the alternating current by means of a contact maker mounted on a shaft and the arrangements of connections as shown in Fig. 88. A temporary contact maker which works sufficiently well can be made by turning up a wooden collar split in two halves to fit around the shaft as shown in Fig. 88, and held in position by a tightly wound band of copper wire. This band is sweated to a small strip of copper let into the wooden collar. A small brush is now arranged on a rocking arm to make contact with the strip when it passes and another brush is arranged to make permanent contact with the copper band. The connections to this contact maker are shown in Fig. 88. Two resistances, fed from a source of continuous current, preferably a battery, are arranged as a potential divider, and for each position of the rocking brush the potential divider is adjusted until no deflection is obtained upon the galvanometer *G*. The reading of the voltmeter *V* is then a measure of the difference of potential between the journal and the bearing at the instant when the contact maker is passing the brush. By rocking the brush the wave form of the potential difference can be mapped out. In cases where a fairly large alternating current can be obtained from the shaft we may use the contact maker to plot out the wave form of the alternating current by balancing the drop of pressure in an ammeter shunt. When we have discovered the exact conditions under which the current flows, the frequency of the current and its phase in relation to the position of the poles, and any other feature of the machine liable to set up an E.M.F. in the shaft, there usually will be very little difficulty in assigning the true cause.

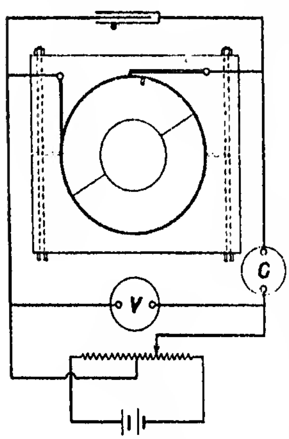


FIG. 88.

Cure—Homopolar effect.

Permanent magnetisation of the shaft is rarely sufficiently severe to set up an injurious current by homopolar effect. If, by reason of some marked dissymmetry, the magnetisation of the shaft is very severe, the right cure is to get rid of the dissymmetry. Sometimes the homopolar effect only occurs at instants of short-circuit of the machine, and the causes of short-circuit can generally be removed.

Transformer effect.

A transformer effect arising from a dissymmetry can be cured by the removal of the dissymmetry. Causes (5), (8) and (9) are difficult to remove. The course generally adopted is to insulate the pedestal of the bearing so as to make a break in the (*a*) circuit. This is a very effective method of stopping the flow of the current in the shaft. In insulating the pedestal it is of course necessary to insulate the holding-down bolts, and where the E.M.F. producing the current is fairly high, any oil-supplying pipes should also be insulated. It is sufficient to insulate one pedestal.

MECHANICAL DEFECTS.

The following mechanical defects may occur in either A.C. or C.C. generators or motors, and should therefore be considered in this chapter:

Defective supporting fingers.

The finger-plates that are used to support the laminations of the teeth at the ends both of the stator and of the rotor of dynamo-electric machines must be carefully designed if they are to perform their function properly. A very considerable pressure is required to keep the laminations of the teeth so tight that they do not vibrate laterally. Sometimes, during the process of pressing up the laminations, the fingers of the finger-plates are bent outwards; and when the pressure is taken off, the laminations of the teeth are so loose that they can vibrate under the magnetic forces that come upon them during the operation of the machine. Although the amplitude of the vibration of the laminations may be small, the frequency is so high that the metal may become fatigued and the laminations may break off one by one. The breaking-off of a lamination upon a single tooth may lead to very serious trouble, for it may catch against the edge of a pole and be driven through the insulation.

The looseness of the punchings may arise either from the fingers having been bent by some accident or by a finger being originally too weak in design. Another cause sometimes occurs on machines whose laminations consist of a number of sectors held in dovetails

in the frame. If the dovetails have not been machined with sufficient accuracy, it may be that when the laminations are built up they take a wavy formation; so that while some of the fingers may be pressed with undue pressure against the crest of a wave, other fingers in the trough of a wave barely touch the laminations.

An armature core loose on one side and tight on the other can occur through defective rolling of the sheet iron of which it is built. A big sheet may be thicker in the middle than at the edges. If now each sheet provides two circular punchings these will be thick at one point of the circumference and thin at a point diametrically opposite. A case of this kind was brought to the attention of the author where by some unlucky chance most of the punchings had the keyway punched in the same position relative to the thick part. As a consequence the core was very tight at one point and very loose at the other. Attention was drawn to the matter on account of the large balance weight required to balance what was thought to be a perfectly symmetrical armature.

After a machine is erected and before the rotor is put in position, all the teeth should be inspected to see whether the punchings are properly tight. If there is any sign of looseness, the defect must be remedied.

Cure for loose tooth laminations. Where the finger-plates have been designed with sufficient mechanical strength and the looseness is due to some such accident as above described, the laminations may be tightened by driving in a number of hardwood wedges cut so as to have a width almost equal to the width of the tooth. These wooden wedges should be driven well under the working face of the armature by a drift, and positively prevented from coming out by bending over and bruising the edges of the laminations flanking each wedge. Each wedge should not be more than 0·05 inch thick. Another plan sometimes adopted is to pack a mixture of plaster-of-Paris and shellac varnish, mixed to the consistency of paste, between the punchings; this can be driven in by means of a blunt knife.

Where the fingers are of insufficient mechanical strength, new fingers must be inserted. This is sometimes a very expensive matter. It can sometimes be done without rewinding the machine. Any attempt to fix new fingers without removing the end-plate must be made on the soundest mechanical principles, for if one of the fingers should come loose the winding will probably be destroyed. In cases where a number of tooth laminations have already broken off, the space should be filled with a fibre block fitted so as to preserve the pressure upon the laminations flanking it, and secured in a thoroughly good mechanical manner.

Ventilating Ducts.

It sometimes happens that a ventilating plate, intended to preserve a space between laminations so as to form a ventilating duct, has not sufficient mechanical strength and gives way under pressure applied to the punchings. In these cases it is first of all necessary to consider whether the ventilating duct is needed for the operation of the machine. Sometimes an armature runs quite cool enough without ventilating ducts; then all that need be done is to see that the crushing of the ventilating plate is not leading to any other mechanical defect. In cases where the machine is not cool enough and where it is not possible to provide sufficient ventilation without the ducts, there is no alternative but to rebuild the armature with new ventilating plates properly designed.

Sometimes in induction motors having very short air-gaps, the ventilating ducts in the rotor and stator, which were intended to be in line with one another, are through defects in building not in line. If the ventilation of the machine is seriously interfered with, owing to the inability of the air from the rotor ducts to get along the air-gap in sufficient quantity, the defect can sometimes be minimized by grinding off the edges of the punchings flanking the ducts, so as to make the air-gap a little wider just at that part. Where the laminations are built up of segments supported by the dovetails, and the dovetail grooves have not been accurately cut, a wavy shape may be given to the ventilating ducts, which leads to a slight increase in the iron loss. It is very difficult to remedy such a defect without rebuilding the whole machine; but it may be mitigated by a judicious grinding-off of the corners of the iron on the crests of the waves.

Loose punchings.

An armature core consisting of complete rings built on a shaft or a spider should be designed so as to have a very tight fit on the shaft or spider. The laminations should be keyed in a very positive manner so that there is no danger of the shearing of the metal. It sometimes happens that the design or manufacture is not satisfactory in this respect. When the machine is up to speed there may be evidence that the armature core is loose on its support. In the case of an induction motor having a short air-gap, the movement of the punchings may lead to a dissymmetry in the gap. In the case of C.C. machines, the looseness of the core may lead to relative motion between the conductors and the commutator; and even where the keying of the punchings is satisfactory, the rapid bending of the conductors at the commutator necks may result in fatigue of the metal and ultimately in open circuits. If the key is not strong enough to hold the core in place, the whole

winding may be destroyed through relative motions between the core and the commutator. Sometimes a core may be fairly tight *when cold and stationary; but the combined action of centrifugal* forces and rise of temperature may make it loose enough to cause trouble.

A loose core can sometimes be tightened without rewinding the machine by drilling holes between the spider and the punchings and driving wedges into these holes.

Defect in bolts holding the core.

On many machines the pressure on the core plates is maintained by means of bolts. These bolts must be insulated with insulation that is mechanically extremely strong. Cases have been known* in which the vibration of the machine set up vibration in the bolts, and as the natural period of vibration of the latter happened to correspond with the period of the impressed vibration, resonance was set up (see page 124) which resulted in the breaking down of the insulation of the bolt notwithstanding its very substantial nature. To avoid this, the frequency of vibration of the bolt should be roughly calculated, and care taken that it does not correspond with the frequency of revolution or of the passage of the poles. It is best to have the frequency of vibration of the bolt higher than that of any impressed vibration; but this may not always be possible. If the bolts and their insulating tubes are a tight fit in their holes, the vibration will be better damped than if they are a loose fit.

Loose spider.

In a cast-iron spider sometimes there are internal stresses set up when it is cooling after being cast. If these stresses have not been relieved by annealing, they may result in cracks in the spider arms; or, where sufficient allowance has not been made for the press fit in the boring out of the central boss, the whole spider may become loose on the shaft. This is an accident that not uncommonly occurs with the spiders of commutators; and it may lead to very troublesome looseness of the whole commutator, the reason of which is not always apparent at first sight. If the spider arms are perfectly sound, the spider can usually be tightened by means of keys.

Insufficient support of insulation.

Most of the insulating materials used in the construction of dynamo-electric machinery have very poor mechanical properties and cannot always be relied upon to support even their own weight. This is particularly true of all materials held together by gums and

* See *Engineering*, 18th Feb. 1921, p. 198.

varnishes, such as built-up mica. Wherever built-up mica tubes project from slots, the projecting part should be taped with linen or cotton tape, the ends of the tape being properly secured by sewing or other permanent mechanical means. Where micanite washers are used to insulate field-coils, some auxiliary support such as tape, judiciously wound around the micanite, is necessary in order to ensure that flakes of mica shall not be frayed out and come away piece by piece. In high-speed rotors it is well to protect the slot insulation of all parts where the insulated conductor crosses a ventilating duct. In turbo field rotors this is sometimes done by lining the slot with a thin cell made of tinned iron, which not only prevents the insulation from bulging out into the ventilating duct and cracking itself on the corners of the duct, but also protects it from the bombardment of small particles of dust that pass through the rotor at great speed and may in time damage it.

Loose coils.

The field-coils of C.C. machines and synchronous converters should always be secured so firmly that there is no chance of their becoming loose under the action of vibration and high temperature. If a field-coil is loose, it may be that constant movement will wear through the insulation and cause a fault.

Where armature coils are not very well secured in their slots, there may be a relative movement between the coil and the core, which endangers the insulation, and may lead to the breaking of copper connecting leads through vibration and fatigue.

Causes of breakdown of insulation.

It is not proposed to deal with this matter fully in this book. The many possible causes of failure arising from defective design, defective construction, defective material, ill usage, relative motion between parts, vibration, abrazion, overheating, dampness or dirt are sufficient to form the subject matter of a large volume. The reader is therefore referred to the text books * on the subject.

It may be of interest to mention a cause of breakdown which at first sight appears to be very innocent, but which nevertheless may be very treacherous. If by any chance a minute iron filing finds its way to the inside of a micanite tube, forming the insulation of an armature coil, it may cause the ultimate breakdown of the tube. Turbo generators are often wound with a single conductor per slot, and though it may be necessary to laminate the conductor in order to reduce eddy-currents in it the voltage between strands is not so high as to call for scrupulous care and cleanliness in insulating the

* Fleming and Johnson, *Insulation and Design of Electrical Windings* (Longmans); Turner and Hobart, *Insulation of Electrical Machines* (Whittaker).

various strands. A half sticky mass of insulated strands can easily pick up an iron filing from a bench and the conductor may be placed in its insulating tube without the filing being noticed. All may be well if the filing is so embedded in sticky compound as to remain immovable, but if it becomes free it will vibrate and rotate under the action of the magnetic field produced by the combined action of the current in the conductor and the main magnetic field.

This usually constitutes an elliptically rotating field which in big turbo generators may attain a maximum intensity of about 1500 C.G.S. units.

Experiments made with the direct intention of investigating this matter have demonstrated that a rotating field having a maximum intensity of not more than 200 C.G.S. units is sufficient to keep a minute iron filing spinning on its bed of mica. If it spins it wears the mica and in time may make a hole right through it. In one experiment a filing weighing half a milligram rotating in a field of 600 C.G.S. units drilled a cavity more than ·02 cm. in mica in the course of four hours. It is known that holes have been drilled right through micanite tubes 3 millimetres in thickness in the course of several years' service. The rotating filing seems to be the most likely cause. It would appear that a filing inside the tube is very much more dangerous than a filing outside the tube, because when inside it is kept up against the mica by the attraction of the iron teeth, whereas if it is outside it sticks to the teeth and cannot do more than make little pock marks. These pock marks have often been observed on the outside of micanite tubes. They are more likely to be due to iron filings than to electrostatic discharge.

Another possible cause of breakdown of insulating tubes is the movement of the individual conductors within the tube. In cases where the conductors have not been sufficiently pressed together and secured, the electro-magnetic forces upon the conductors may be sufficient to keep them in constant vibration when the machine is on load. This may lead to a wearing away of the mica and the ultimate breakdown of the tube.

NOISE.

The noise made by a machine may arise from a source which is either (*a*) magnetic, (*b*) mechanical, or (*c*) pneumatic.

(*a*) **Magnetic source of noise.** It is easy to tell when a sound has its origin in some magnetic cause, because it is not produced when the machine is running at full speed and is unexcited. It may be that the sound comes on as soon as the exciting current flows or it may be that it is not until load comes on that the noise is very serious.

The armature teeth of D.C. generators or motors very often set up vibrations in the horns of the poles, and in the teeth themselves, by the magnetic attraction between the corners of the teeth and the poles as they revolve. This noise may be very loud at full excitation and almost die away at lower excitations. It commonly increases as the load increases, owing to the distortion of the field and consequent saturation of the teeth under the trailing horns. In cases where it is very bad there may be some contributory cause, as where the natural period of vibration of the parts resonates to the frequency of the note produced. After it is established that the noise is magnetic the frequency of the note should be taken as explained on page 153, and if this corresponds to the frequency of the teeth, the cause will be sufficiently evident.

A magnetic noise of this kind can generally be cured by putting a deeper bevel on the pole. If the bevel is already very deep, it may be that the corners of the teeth are attracted by the inside corner of the bevel. If this is so the corner should be removed.

The most perfect cure for this kind of noise is to skew the teeth or the edge of the pole shoe by exactly one slot pitch. The skewing of the teeth can of course only be done when the armature is being built. The skewing of the pole shoe is sometimes possible on a completed machine.

The teeth of an induction motor sometimes hum under the action of magnetic attraction. The note produced may have the frequency of the passage of rotor teeth past stator teeth or the passage of stator teeth past rotor teeth, or it may correspond to nothing at all inside the motor, being produced by ripples in the wave form of the E.M.F. supplied to the motor terminals. In a case which came to the knowledge of the author a certain induction motor set up a very troublesome noise when run from one source of power, but when run from another source of power it was almost silent. It was found that the first source of power had very marked higher harmonics of a frequency that set up a loud humming in the stator core. In investigating troubles of this kind the first step is to find out whether the noise has a magnetic origin. This can be done by running the motor light and listening to the noise as the circuit breaker is opened. If the noise stops instantly it has a magnetic origin, but if it subsists until the motor speed drops its origin is mechanical or pneumatic. The frequency of the note should then be measured as described on page 153. When the frequency is known there is generally very little difficulty in assigning the cause.

After the cause is known it may be a very difficult matter to effect a cure without carrying out expensive changes in the construction. Sometimes a noise is produced by the rotor not being central and causing undue saturation of some of the stator teeth.

This can easily be remedied. Sometimes part of the stator punchings vibrates between the supports. It may be possible to stop this by drilling into the frame and wedging the punchings more securely. Small motors which can be completely dipped and impregnated with petroleum residue will be found to run more quietly after being impregnated. Where the frequency of the note points to its origin being in the generator supplying the power, it may be necessary to remove the ripples in the supply voltage (see p. 204).

The buzzing of punchings, when the finger-plates intended to secure them at the ends of the armature are not perfectly effective, is a magnetic noise which is not very loud, but of the greatest importance in giving us warning of a serious defect. Every erecting engineer should be on the look-out for buzzing punchings, and have the trouble remedied at once (see page 146), or the loose teeth may break off and pierce the insulation.

Another kind of noise may arise when one of the poles of a **field magnet** is **short-circuited** or partly short-circuited. This will set up vibrations and the consequent noise may be the first indication of the trouble.

When one of the phases of the **rotor** of an induction motor is **open-circuited** it may emit a grunt having the frequency of the slip. The low frequency at once leads us to suspect something in the rotor and to apply the tests for open circuit (see p. 36).

(*b*) **Mechanical source of sound.** One of the commonest examples of this source of noise is the screeching of brushes on a commutator. The noise generally has a note whose frequency corresponds to the frequency of the commutator bars. This is especially so when the mica has been cut out. The usual cure is to employ graphitic brushes having good lubricating qualities. The brushes should be as wide as possible consistent with good commutation. The adjustment of the tension of the brushes often makes a change in the noise. Various tensions should be tried. Sometimes the very smallest changes in the condition of the surface of a commutator will make an enormous difference in the amount of noise produced.

The application of a small drop of oil or a touch of paraffin wax may silence a most noisy brush gear, but its effect does not last long. A highly polished commutator may make very much more noise than one that has been recently scratched with glass paper. What is said in Chapter IX. about chattering of brushes has a direct bearing on this kind of noise. A diminution of the chattering will be accompanied by a diminution of the noise. Sometimes the noise proceeding from a commutator depends for its loudness upon some acoustic resonance of cavities between the commutator lugs. In one case within the experience of the author a very noisy commutator was improved by fixing wings of press-spahn to the brush arms so that

they covered some of the spaces between the commutator lugs though they were ¼-inch away from the lugs. No one was able to say why this reduced the noise. The effect was discovered by accident.

There are many other mechanical noises and rattlings that may occur in dynamos whose cause is sufficiently obvious as soon as the noise is heard.

(c) **Pneumatic source of sound.** The air issuing from the numerous openings in the ventilating plate of a rotor or between the ends of the conductors may form a syren with other openings in the stator and produce a very loud sound. The pitch of the note is a guide to the particular cause of the trouble. Where some doubt exists as to which ventilating duct or other part is at fault, we may adopt the plan of keeping away the air from the part suspected. This can sometimes be done by packing pieces of cotton cloth into the inside opening of the duct. Cotton cloth is better for this purpose than cotton waste. The latter unless carefully used may lead to other trouble. By a process of elimination the faulty part can be detected.

If the ventilation of the machine is good enough without employing the draught through the noisy part the simplest plan is to stop or reduce the air supply to that part. Where the draught through the noisy part is essential for the cooling of the machine, the matter may be more difficult to deal with. Experiments should be made to see if there are any cavities that are resonating to the note in question. It is sometimes found, for instance, that the air from the ventilating ducts of the rotor of an induction motor makes a loud whistling sound, the note corresponding to the frequency of the rotor slots, while a very similar rotor placed in a stator of different construction will be almost silent. The difference lies in the size and shape of the cavities in the stator ventilating ducts. In one case the cavities resound and in the other they do not. Small changes in the shape of the cavities by the introduction of pegs of bakelized paper well secured to the frame may be sufficient to stop the resonance and reduce the noise.

Measurement of the frequency of a note.

Some experimenters have such a good musical ear that they can recognize the note made by a machine, and give it its name on the true scale of C. Others may be able to borrow a set of marked tuning forks, and recognize the note by comparison or place it somewhere between the notes of two forks. When the name of the note and the octave to which it belongs is known, the number of vibrations per second can be ascertained from a table like that given below.

TABLE.

Number of vibrations per second in musical notes in the true scale of C, taking the middle C^1 at 256 per second.

Name of Note.	Lower Octaves.		Middle Octaves.		Upper Octaves.	
C	...	64	128	256	512	1024
C♯ D♭	...	67	135	270	540	1080
D		72	144	288	576	1152
D♯ E♭		77	153	307	614	1228
E	40	80	160	320	640	1280
F	43	85	170	341	682	1364
F♯ G♭	45	90	180	360	720	1440
G	48	96	192	384	768	1536
G♯ A♭	51	102	205	410	820	1640
A	53	107	213	427	854	1708
A♯ B♭	57	115	230	461	922	1844
B	60	120	240	480	960	1920

Where a number of investigations have to be made into the frequencies of notes, as for instance in the hunt for the causes of disturbance in telephone circuits, the best plan is to make up a little high frequency alternator of the inductor type from an ordinary iron spur wheel. This little machine when run at different speeds and connected to a telephone will give any note required and the frequency of the note can be calculated from the speed of the machine and the number of the teeth on the spur wheel. In the case of telephone disturbances it is convenient to connect the telephone line containing the note so measured in series with the armature of the little alternator and a telephone. The alternator is then excited to give a note of about the same loudness at the telephone circuit, and the speed is changed until almost perfect synchronism of the two notes is shown by the slowness of the beats.

CHAPTER V.

ON THE USE OF VECTOR DIAGRAMS.

ONLY a small proportion of erection and trouble engineers make use of vector diagrams when attacking alternating-current problems. The reason appears to be, that they have not enough confidence in the answer they get when they use these diagrams. If we enquire further into the want of confidence in the result, we shall find that it is generally caused by uncertainty as to the direction in which the various vectors shall be drawn; this is especially so in the case of polyphase diagrams. It is so important to anyone who wishes to understand a polyphase problem that he should be able to construct vector diagrams with the certainty of getting a correct result, that the author has thought it worth while to introduce here a few hints that he has found useful, in the hope that they may prove useful to others.

Doubt is sometimes expressed upon the applicability of the vector diagram to the representation of alternating currents and voltages that do not follow a sine law. Dr. W. E. Sumpner has shown * that the vector diagram is applicable to represent alternating quantities that do not follow a sine law. The length of the vector that is taken in any particular case may represent to scale the square root of mean square (or virtual) value of the quantity under consideration; and the phase angle, ϕ, between a voltage and a current can be defined as the angle whose cosine gives the ratio between the true power as measured by a wattmeter and the apparent power obtained by multiplying the virtual value of the voltage by the virtual value of the current. The reader is referred to Dr. Sumpner's paper for the proof of this important proposition. From the practical point of view it is sufficient for the engineer to recognize that he can measure the virtual volts and amperes on alternating-current instruments, thus obtaining the apparent power; and can measure the true power on a wattmeter, thus obtaining the power factor, or $\cos\phi$:

* *Proceedings of Royal Society*, 1897, vol. 61, p. 455; also *Journal I.E.E.*, 1902, vol. 31, p. 630.

hence the angle ϕ is defined independently of any question as to the wave-form of the volts and amperes, or of the relative times at which they reach their maximum values. In defining the phase-angle between two currents, it is only necessary to find by a wattmeter the difference of phase between each current and any given voltage; then the difference between the phase angles with regard to the voltage is the difference of phase of the two currents.

If we are to be able to state with certainty in what direction any particular vector shall be drawn, and to interpret the final result to which our vector diagram leads, we must not fail to draw in the first instance a **circuit diagram**, and to attach suitable arrow-heads to it. By a circuit diagram is meant a plan of the conductors making up the circuit or network under consideration; each line of the diagram representing a conductor having attached to it an **arrow-head**, which defines the direction taken as positive along that conductor. Before one can make any intelligible statement as to the full meaning of a vector, one must fix one's mind upon a particular conductor and see what direction along that conductor one regards as positive. It is possible to obtain a correct solution of an alternating-current problem, whatever direction we take as positive along any of the conductors under consideration; that is to say, it is not necessary to adopt a symmetrical system of placing our arrow-heads; but if we are wise we shall always choose a symmetrical system, because by so doing we are much less likely to make mistakes.

In giving some examples of the use of circuit diagrams and vector diagrams, it will be well to begin with the very simplest case.

EXAMPLE 1. **Single-phase simple circuit.**

Fig. 89 is a circuit diagram representing the simple circuit of an alternator connected to a resistance and choke coil. An arrow-

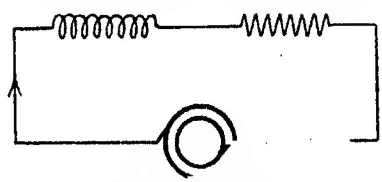


FIG. 89.—Circuit Diagram.

head has been fixed to the diagram, which points around the circuit in a clockwise direction. In this case the direction is perfectly arbitrary: we could work equally well with an arrow-head pointing in a counter-clockwise direction; but, the arrow-head having been once fixed, the vector diagram shown in Fig. 90 has a perfectly

definite meaning. Two vectors, OV and OA, are supposed to revolve about O in a counter-clockwise * direction.

It is necessary to know the scale on which the vectors are drawn. According to the original conception of the vector diagram as a representation of an alternating quantity, the length of the vector represents the maximum value of the quantity in question; so that when it is rotated about its centre, making one revolution per cycle, its projection upon the vertical gives to scale at each instant of time the instantaneous value of the quantity. If, for instance, the alternator (Fig. 89) generates a voltage 423 sin ωt, we might

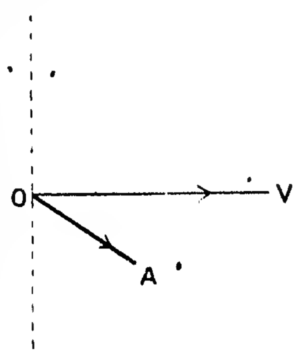


FIG. 90.—Vector Diagram.

adopt the scale 1 centimetre = 100 volts, and draw the line OV 4·23 cms. long to represent the maximum of 423 volts. Then if we give the vector OV an angular speed of ω about 0, the projection of OV on the vertical will give at each instant of time the instantaneous value of the generated voltage. For the practical use of vector diagrams, however, it is only rarely that we wish to know the instantaneous value; we are mainly concerned with the virtual values of the quantities and with their phase relations. It is therefore more convenient to let the vector represent to scale the virtual value of the quantity; so that the voltage in Fig. 89 would be represented by the vector OV in Fig. 91, which is 3 cms. long. To arrive at instantaneous values, we must then multiply the projection upon the vertical by $\sqrt{2}$. The vector OA may represent 150 amperes virtual lagging by 30° behind the voltage, the scale being 1 cm. = 100 amperes. It is sometimes convenient to draw thick lines for current and thin lines for voltage; other convenient methods may be adopted for distinguishing between different kinds of quantities. We now come to the question of the arrow-head in Fig. 89: it must be remembered that when we make a statement to the effect that $V = 423 \sin \omega t$, the time t in seconds is supposed to be measured from a certain datum instant; and at this same instant the vector diagram is supposed to start from the position shown in Fig. 91. Let the frequency $f = 50$; then $\omega = 2\pi f = 314$ radians per second. In $\frac{1}{314}$th of a second after the fixed datum, the clock diagram will have moved through one radian and have arrived at the position shown in Fig. 92. The projection, then, of OV and OA is positive

* The counter-clockwise direction for the rotation of a vector diagram has been fixed by the International Electrotechnical Commission.

in both cases; that is to say, that at $\frac{1}{314}$th of a second after the datum instant, the E.M.F. in the circuit in Fig. 89 is tending to drive current in a clockwise direction, as indicated by the arrow-head, and the current at the same instant is flowing in a clockwise direction. *If we had fixed our arrow-head so that it pointed in a counter-clockwise direction, then the vector diagram in Fig. 92 would mean that*

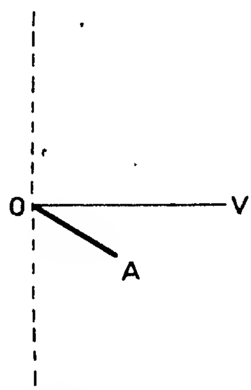


FIG. 91.—Vector diagram representing virtual values.

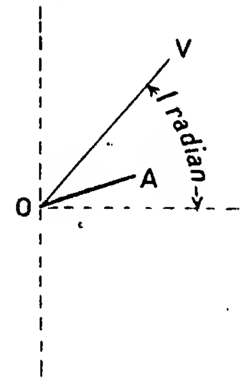


FIG. 92.—Vector diagram when $\omega t = 1$.

at the instant in question the voltage and current in Fig. 89 are in a counter-clockwise direction. This matter is so simple when we deal with a simple circuit, that a statement of the matter such as given above appears to be childish; nevertheless it is only by a strict adherence to the use of arrow-heads, and a constant reference of the mind to what they mean, that we can hope to deal successfully with more difficult problems.

EXAMPLE 2. **Three-phase power measurement.**

Let us now take the case of the measurement, by the two-wattmeter method, of the power delivered by a three-phase star-connected generator. Fig. 93 is our circuit diagram. It is common practice, when drawing the circuit diagram of a three-phase star-connected machine, to draw the wires representing the three phases as if they were 120° apart. This sometimes makes a confusion in the student's mind between the circuit diagram and the vector diagram; in fact, it is not uncommon for engineers who are familiar with the subject to draw one figure to represent both diagrams. It is desirable to avoid this confusion. It will be seen that the arrow-heads on the three legs of the star have been drawn pointing outwards; it does not matter whether we make them point outwards or inwards, but it is advisable to make them all point one way, so as to preserve symmetry in the vector diagram. When we come to attach the arrow-heads to the voltmeter connections of the wattmeter, we

shall find that it is convenient in this case to place the arrow-heads as shown in Fig. 93.

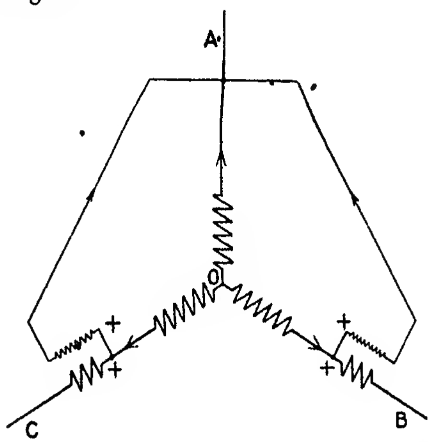


FIG. 93.—Circuit diagram for the two-wattmeter connections.

We must be very strict in our convention in the connection of the wattmeter terminals. Most wattmeters have a + sign on one of the voltage terminals, and on one of the current terminals; this + sign means that if the wattmeter is connected to a D.C. circuit in such a way as to make the + terminals both positive or both negative, the wattmeter needle will move over the scale; whereas if one + terminal is positive and the other negative, the wattmeter needle will tend to move in the opposite direction. In connecting the wattmeter to the three-phase generator, the positive terminal of the voltage circuit and the current circuit should be arranged as shown in Fig. 93. If this is done, we know that when the current in the leg B is flowing in the direction of the arrow-head and V_{ba} is also in the direction of the arrow-head, the wattmeter will read positively. If the wattmeter in leg C is also arranged with the + terminals as shown in the figure, when there is a current in C flowing in the direction of the arrow-head and the voltage V_{ca} is in the direction of the arrow-head, the wattmeter will tend to read in a positive direction.

We can now proceed to draw the vector diagram of the voltages and currents in the generator. We may represent the three voltages V_a, V_b and V_c generated in the respective phases of the generator by the three lines OV_a, OV_b and OV_c 120° apart. The voltage V_{ba}, as drawn with the full line in Fig. 94, is then made up of V_b taken positively and V_a taken negatively, because the arrow-head on phase A (Fig. 93) is opposed to the direction of the arrow-head V_{ba}. In our clock diagram, therefore, we must set off the line V_bV_{ba} in the

opposite direction to the vector OV_a; we thus arrive at the vector OV_{ba}, which represents the pressure in the volt circuit of the wattmeter taken on the convention of the arrow-heads shown in Fig. 93. If the arrow-heads on V_{ba} had been taken in a clockwise direction in Fig. 93, our vector diagram would have come out as shown by the dotted line in Fig. 94. The meanings of the two results are identical: the full line shows a one voltage in a counter-clockwise direction, and the dotted line shows an opposite voltage in a clockwise direction.

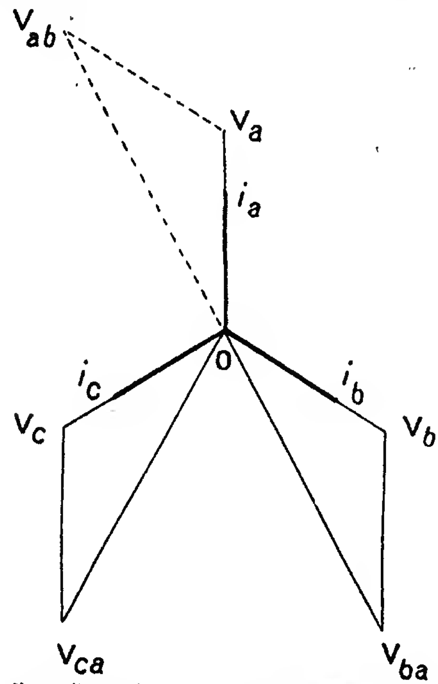


FIG. 94.—Vector diagram for the two-wattmeter method. Power factor = 1.

In view of the fact that the positive ends of the volt coils in both wattmeters are connected to the terminals B and C of the machine, it is convenient to place an arrow-head on the volt circuits as shown in Fig. 93; so that a current flowing in the direction of the arrow-head will be a positive current in the volt coils. Taking now the ordinary proof of the two-wattmeter method, we have:

$$i_a + i_b + i_c = 0,$$
$$i_a = -i_b - i_c.$$

The total power generated in all three phases at any instant

$$= W = V_a i_a + V_b i_b + V_c i_c.$$

Substituting for i_a, we have

$$W = i_b(V_b - V_a) + i_c(V_c - V_a).$$

Fig. 94 gives the phase position of the voltages and currents in a balanced circuit working on unity power factor. The currents i_a, i_b and i_c are in phase with their respective voltages. The vector $V_{ba} = V_b - V_a$; and the vector $V_{ca} = V_c - V_a$. When the diagram (Fig. 94) is in the position shown, i_b is negative and V_{ba} is negative; so that with the connections shown the wattmeter in phase B will have a positive torque. The same is true of the wattmeter in phase C. Thus the sum of the readings of the wattmeters gives the total power. If now the current lags by 60° behind the phase E.M.F. (as shown

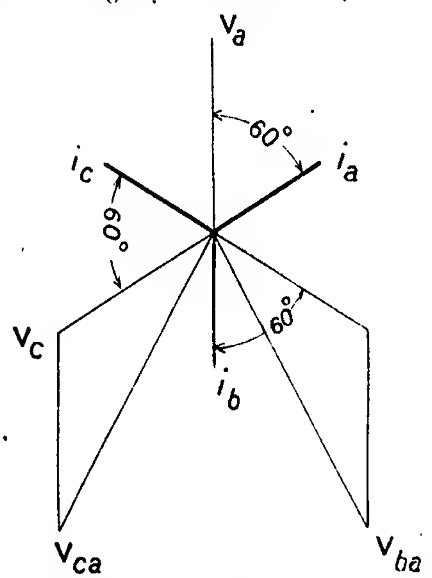


FIG. 95.—Vector diagram for the two-wattmeter method. Power factor 0·5.

in Fig. 95), the wattmeter in phase C will read zero, because the current is lagging 90° behind V_{ca}; while the wattmeter in phase B will read the same as on unity power factor. If the current lags more than 60°, the C wattmeter will read negatively, and its connections will have to be reversed in order to bring the pointer upon the scale. It is then necessary, of course, to subtract the reading of wattmeter C from the reading of wattmeter B in order to ascertain the power. It will be seen that by adopting a strict convention as to the signs, taking proper care with the connections of the wattmeter to the three-phase circuit, the tester can tell whether the wattmeter readings have to be added or subtracted and whether the wattmeters are reading

power generated by the machine under test or power absorbed by the machine under test. This a tester should always be able to do from an inspection of his connections, independently of any other information he may have. Sometimes there are very mysterious happenings in the behaviour of polyphase machinery: a motor sometimes behaves as though it were a generator, and a generator as a motor. Great difficulty may arise in clearing up the trouble if the tester is not able to say definitely from his connections whether a wattmeter reading indicates power supplied or power absorbed.

EXAMPLE III. **The balancing of a three-phase circuit by means of a choke coil.**

Another example of the convenience of the vector-diagram method in solving problems that would be rather difficult without it is the case given below, in which a three-phase system that has been thrown out of balance by the addition of a single-phase load of low power factor has its balance restored by the addition of a choke-coil. Let us consider a three-phase system in which the voltages measured from the star-point to the terminals are:

$$e_a = E_a \sin(\omega t - a_a),$$
$$e_b = E_b \sin(\omega t - 2\pi/3 - a_b),$$
$$e_c = E_c \sin(\omega t - 4\pi/3 - a_c),$$

and in which the currents in the three legs are:

$$i_a = I_a \sin(\omega t - \phi_a),$$
$$i_b = I_b \sin(\omega t - 2\pi/3 - \phi_b).$$
$$i_c = I_c \sin(\omega t - 4\pi/3 - \phi_c).$$

Then the voltages are in balance when

$$E_a = E_b = E_c, \quad \text{.......................................(1)}$$

and

$$a_a = a_b = a_c. \quad \text{.......................................(2)}$$

In a mesh-connected system the angles between the voltage vectors are dependent upon the values of the voltages, because the vector sum of the voltages must be zero. In this case (1) and (2) are not independent. We may, however, consider the star-connected case where the phase angles are independent of the voltages.

The currents are in balance when

$$I_a = I_b = I_c, \quad \text{.......................................(3)}$$

and

$$\phi_a = \phi_b = \phi_c. \quad \text{.......................................(4)}$$

In a three-phase star-connected system not provided with a fourth wire, the phase angles of the currents are dependent upon the values of the currents, because the vector sum of the currents must be zero. Therefore conditions (3) and (4) are not independent. We may, however, consider the perfectly general case where a fourth wire is provided and where the currents and angles are independent.

In a single-phase circuit in which the voltage is $e = E \sin \omega t$, and the current is $i = I \sin(\omega t - \phi)$, the expression for the power is

$$p = \tfrac{1}{2} EI \cos \phi - \tfrac{1}{2} EI \cos(2\omega t - \phi).$$

The first term represents a constant flow of power. The second term represents a double-frequency alternating flow.

Let us assume that in the above-described three-phase system $a_a = a_b = a_c = 0$, that is to say, that the voltages are 120° apart. We may regard the current in each phase as a single-phase load on that phase; so that the power in leg A is

$$p_a = \tfrac{1}{2} E_a I_a \cos \phi - \tfrac{1}{2} E_a I_a \cos(2\omega t - \phi_a).$$

The power in leg B is

$$p_b = \tfrac{1}{2} E_b I_b \cos \phi - \tfrac{1}{2} E_b I_b \cos(2\omega t - 4\pi/3 - \phi_b).$$

And the power in leg C is

$$p_c = \tfrac{1}{2} E_c I_c \cos \phi - \tfrac{1}{2} E_c I_c \cos(2\omega t - 2\pi/3 - \phi_c).$$

In each of these expressions the negative term represents a double-frequency alternating flow of power. If now the phases are balanced so that $E_a = E_b = E_c$, $I_a = I_b = I_c$, and $\phi_a = \phi_b = \phi_c$, these alternating terms can be represented by three equal vectors spaced at 120° to one another, which rotate at twice the frequency of the supply (see Fig. 96). As the sum of equal vectors so placed is equal to zero, the alternating components of the power balance one another when taken for the system as a whole. Thus we get, as Steinmetz has pointed out,* another criterion of the balance of the loads. If the sum of the three alternating components of the power is zero, the load is balanced in the sense that the single-phase load is on the whole eliminated and the power flows from the generator in an even stream; but if the sum is not zero there is a fluctuating flow of power from the generator.

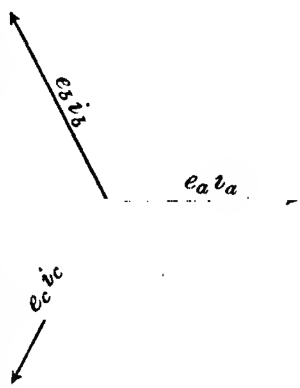


FIG. 96.—Vectors representing balanced power rotating at double speed.

Elimination of single-phase power components without 'balance of phases.' If the conditions (1), (2), (3) and (4) above do not obtain, then the alternating components of the power may or may not balance out one another. It may happen by chance or design that

* *The Theory and Calculation of Electric Circuits*, p. 314.

the amplitude and phase of three alternating power components are such that the three vectors representing them would form the sides of a triangle, with the arrowheads (showing the sense of the vectors) following one another consecutively. In this case the alternating components of the power balance one another, although it may be that neither the currents nor the voltages are balanced.*

Where a polyphase load has been unbalanced by the addition of a single-phase load, it may be balanced by the addition of a wattless load taken by a choke coil or a condenser. Steinmetz has shown that where a load is unbalanced and the resultant of the alternating components of the power is equal to $\frac{1}{2}EI\cos(2\omega t-\phi)$ it is possible to balance the system (according to his definition of balance) by the addition of a choke coil (of no resistance) fed with a voltage $E'\sin(\omega t-\beta)$, where $\beta=\frac{1}{2}\phi+\frac{1}{4}\pi$ and taking a current $I'\sin(\omega t-\beta-\frac{1}{2}\pi)$, where $E'I'=EI$. Or the system may be balanced by the addition of a capacity fed from the voltage $E'\sin(\omega t-\beta)$, where $\beta=\frac{1}{2}\phi-\frac{1}{4}\pi$, and taking a current $I'\sin(\omega t-\beta+\frac{1}{2}\pi)$.

If we apply this method to the balancing of a three-phase circuit which is carrying a single-phase load, it will be found that for some loads the addition of the choke coil gives a true balance, according to the definition on page 162; but that for other loads the balance (while it is such as to bring to zero the resultant alternating components of power) is not such as to comply with conditions (1), (2), (3), and (4) of page 162.

Graphic construction showing balance of power and balance of phases by means of a choke coil. Let the three-phase system A, B, C, Fig. 97, be loaded† with a resistance and choke coil between the terminals $A-B$. Let the voltages in A, B, and C respectively be represented by the vectors E_a, E_b and E_c in Fig. 98. Taking $e_a=E\sin\omega t$, we have

$$e_{ab}=\sqrt{3}E\sin(\omega t+\pi/6).$$

First let us take the instance quoted by Steinmetz,‡ where the power factor of the circuit AB is such that the current lags $\pi/6-\phi$ behind the voltage, so that $i_{ab}=I\sin\omega t$. The alternating component of the power will be

$$\tfrac{1}{2}\sqrt{3}EI\cos(2\omega t+\tfrac{1}{3}\pi-\pi/6),$$
$$=\tfrac{1}{2}\sqrt{3}EI\cos(2\omega t+\pi/6).$$

* See "The Supply of Single-phase Power from Three-phase Systems"; *Journ. I.E.E.*, vol. 57, p. 129, Appendix II.

† The example given here is the one given by Steinmetz (*ibid.*, page 326). Fig. 98 shows how it is that in this *particular instance* the phases are balanced. In Appendices II. and IV. of the *I.E.E.* paper, vol. 57, pp. 129 and 130, examples are given in which the phases are not balanced, although the single-phase load is on the whole eliminated.

‡ *Ibid.*, p 327.

In order to neutralize this alternating component, we can put in circuit a choke coil fed by a voltage,

$$e' = \sqrt{3}E' \sin(\omega t + \pi/6 - \beta)$$
$$= \sqrt{3}E \sin(\omega t - \pi/6),$$

where $\beta = \frac{1}{2}\phi + \frac{1}{4}\pi = \pi/12 + \frac{1}{4}\pi = \frac{1}{3}\pi.$

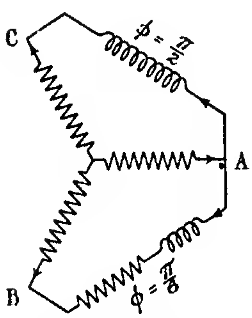


FIG. 97.—Single phase inductive load balanced by a choke coil.

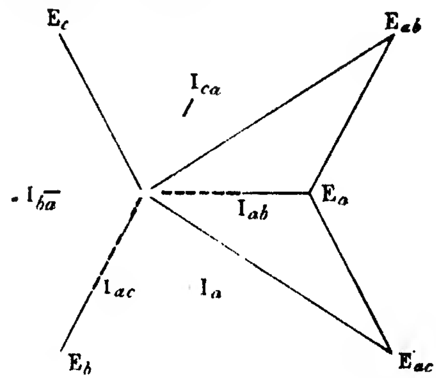


FIG. 98.—Vector diagram for circuits of Fig. 97.

This voltage, lagging 30° behind E_a, can be obtained from the terminals $A-C$, as shown in Fig. 97.

The current through the choke coil is

$$i' = I' \sin(\omega t - \pi/6 - \frac{1}{2}\pi),$$

and if the reactance of the coil be suitably adjusted so that $I' = I$, then the alternating component of the power in the choke circuit is

$$e'i' = \frac{1}{2}\sqrt{3}E'I' \cos(2\omega t - \frac{1}{3}\pi - \frac{1}{2}\pi),$$

and as $\cos(2\omega t - 5\pi/6) = -\cos(2\omega t + \pi/6)$, the two alternating components neutralize each other. Now in this special case it will be seen from Figs. 97 and 98, taking the direction shown by the arrowheads as positive in each leg, that before the choke coil was added the current in leg A was I_{ab}, and in leg B it was I_{ba}. After the choke coil is put in circuit the current through it is I_{ac} in leg A, and I_{ca} in leg C. Adding together I_{ab} and I_{ac}, we get I_a as the current in A. Thus we see that the three legs carry equal currents at 120° apart; and as the voltages were assumed to be in balance we see that conditions (1), (2), (3) and (4) hold.

In applying Steinmetz's method to the case of single-phase load, of any power factor, the question whether or not we get balanced currents depends upon the way in which we build up the voltage $E' \sin(\omega t + \beta)$ from the components selected from the three phases.

Graphic construction showing the **method of choosing** the component voltages from the three phases in order to build up $E' \sin(\omega t - \beta)$, **so as to get balanced currents** in the case of a choke-coil balancer for any power factor.

Let us take the case where the power factor is 0·7. The voltages in the three legs of the star when balanced may be taken as:

$$e_a = 1000 \sin \omega t,$$
$$e_b = 1000 \sin(\omega t - 120°),$$
$$e_c = 1000 \sin(\omega t - 240°).*$$

These are shown in Fig. 100 by the vectors E_a, E_b and E_c respectively. Let the single-phase load be fed from terminals A and C, Fig. 99.

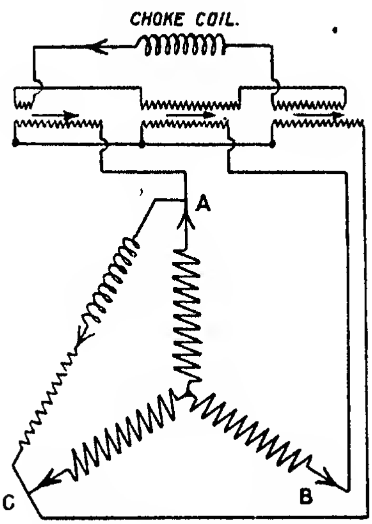


FIG. 99.—Diagram of connections for balancing a single-phase load by means of a choke coil.

$$e_{ac} = 1732 \sin(\omega t - 30°) \quad \text{(see vector } E_{ac}\text{).}$$
$$i_{ac} = 1000 \sin(\omega t - 30° - 45°) \quad \text{(see vector } I_S\text{).}$$

As the arrow-head indicating the positive way through the single-phase load is opposite in sense to the arrow-head on phase C (Fig. 99), the vector OI_S must be reversed (see Oi_c) to represent the current in phase C.

The alternating component of the power is:

$$-\tfrac{1}{2} \times 1{,}732{,}000 \cos(2\omega t - 60° - 45°).$$

* The expression of angles of lag in degrees instead of in radians is adopted for general convenience in what follows. The maximum voltage is arbitrarily taken as 1000 so as to get four significant figures without a decimal point.

In order to neutralize this alternating component by means of a reactive load, we must take

$$\beta=\tfrac{1}{2}\phi+\tfrac{1}{4}\pi=22{\cdot}5^\circ+45^\circ=67{\cdot}5^\circ.$$

Take $e'=1732\sin(\omega t-30^\circ-67{\cdot}5^\circ)$ (see vector $E_c'E'$).

$i'=1000\sin(\omega t-30^\circ-67{\cdot}5^\circ-90^\circ)$ (see vector I').

There are many ways in which we can build up the voltage e'. The problem is to take such components of the voltages E_a, E_b and E_c, by means of transformers having suitable ratios, as will build

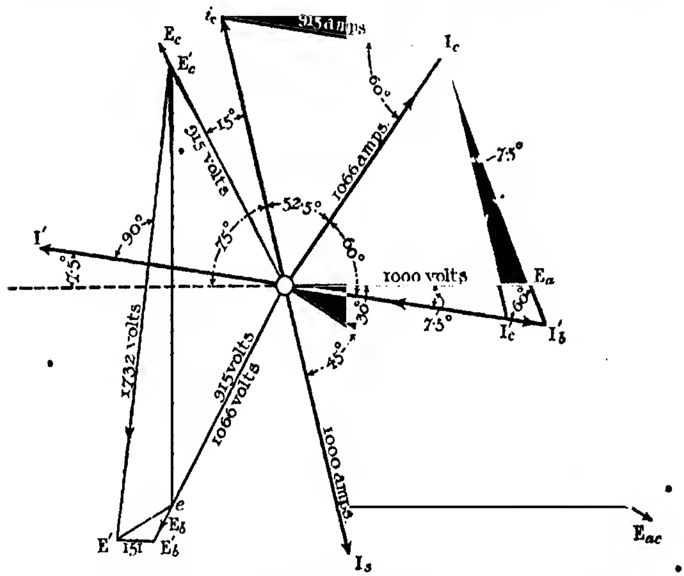


FIG. 100.—Vector diagram showing how to build up the voltage feeding the choke coil in order to balance the currents.

up the voltage e' and at the same time load the system with the transformers in such a way as to balance the currents in the three phases. We begin by laying off OE_a, OE_b and OE_c to scale, the terminal voltage E_{ac}, and the single-phase current of 1000 amperes lagging 45° behind E_{ac}. This is represented by the vector I_s. We also set off the vector E', 1732 volts, the angle being 97·5° behind E_a. This is the voltage that is to be applied to the choke-coil; the current in the choke-coil would be 1000 amperes and would lag 90° behind it. The choke-coil current is given by the vector I'.

Fig. 99 gives the diagram of connections. It is assumed that the primaries of the transformers feeding the choke-coil have all the same number of turns, say 1000. We have yet to find out the number of turns on the secondary of each transformer and its correct polarity.

We note in the first place that phase B does not feed the single-phase load, and therefore feeds only the primary of the transformer. The current drawn by the primary in B must therefore be in phase with the choke-coil current. We see further that if we are to get all the three currents balanced, they must form an equilateral triangle, one side of which (OI'_b) must be parallel to OI'. Again, the vector I_S represents as much of the current flowing in phase A as flows to the single-phase load, the arrow-head on phase A being the same as the arrow-head on the single-phase circuit. In order to represent the current supplied by phase C to the single-phase load, we must reverse I_S, as shown by the vector Oi_c. The problem is now to add to i_c a current which is parallel to OI', such as to give a resultant that will form one of the sides of the equilateral triangle. Similarly, it is desired to add to the single-phase current supplied by I_a, namely I_S, a current also parallel to OI', such that the resultant will form the remaining side of the equilateral triangle. To meet these conditions, it is only necessary to set off the line OI_c at 60° to the line OI'_b and draw the line i_cI_c parallel to $I'O$ until it meets OI_c. I_c is then the apex of the equilateral triangle. The length of the side $OI_c = 1066$ amperes can be scaled off and the triangle OI_cI_b' completed. The side I_cI_b' is then the total current in phase A, and is made up of the single-phase current I_cI_c' and a small current of 151 amperes represented by the vector $I_c'I_b'$. The currents in the primaries of the transformers are directly proportional to the number of turns in the secondaries; therefore the number of turns in the secondary of B shall exceed that of C by a number which shall be equal to the number of turns in the secondary of A. We therefore necessarily have two isosceles triangles, OeE_c' and $eE_b'E'$, built up by the voltage vectors having the sides $OE_c' = Oe$ and $E_b'e = E_b'E'$. The number of turns in the secondaries of the transformers (taking the primaries as 1000) is most easily determined by taking the ratio of the sines of the angles in the triangles $I_cI_c'I_b'$ and Oi_cI_c, as follows:

$$\frac{I_c'I_b'}{I_c'I_c} = \frac{\sin 7{\cdot}5°}{\sin 60°} = 0{\cdot}151,$$

$$\frac{i_cI_c}{i_cO} = \frac{\sin 52{\cdot}5°}{\sin 60°} = 0{\cdot}915,$$

$$I_b'O = 0{\cdot}151 + 0{\cdot}915 = 1{\cdot}066.$$

Therefore the turns in the secondaries of A, B and C are 151, 1066 and 915 respectively. With 1000 volts on each of the three primaries of 1000 turns we get:

$$E_c'O = 915 \text{ volts},$$
$$OE_b' = 1066 \quad ,,$$
$$E_b'E' = 151 \quad ,,$$

and the vector sum of these is $E_c'E'=1732$ volts, which gives us the voltage e' in the correct phase. If now we put in circuit with this a reactance of 1·732 ohms we get 1000 amperes lagging 90° flowing in the secondaries, and this calls for currents in the primaries of the same phase (assuming perfect transformers) the amounts of which are:

Phase A 151 amperes.
,, B 1066 ,,
,, C 915 ,,

If now we add the 1000 amperes I_S in phase A to $I_c'I_b'$, we get 1066 amperes total in phase A; and if we add the 1000 amperes Oi_c to i_cI_c we get $OI_c=1066$, so that all three currents are equal and at 120° to one another. The angle of lag of each current behind its E.M.F. is 67·5° in each case. The alternating components of the power in the three circuits are equal, and the double-frequency vectors representing them are at 120 to one another. They therefore cancel out (see Fig. 101).

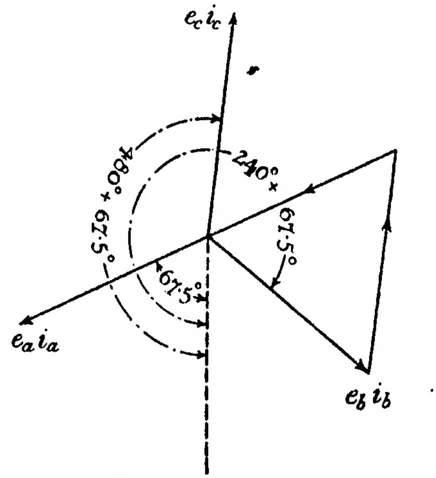


FIG. 101.—Vector diagram of power showing how the three power components are 120° apart.

When we come to connect the transformers in the choke-coil circuit, the vector diagram tells us the polarity of each coil as well as the number of turns. The voltage $E_c'E'$ is built up of the vectors $E_c'O$, OE_b', and $E_b'E'$. As $E_c'O$ is opposed in polarity to OE_c, the 915 turns of the C secondary must be reversed, so that the arrow on the transformer is in opposition to the arrow-head on the choke-coil circuit. The vector OE_b' is of the same polarity as OE_b, therefore the 1066 turns of the secondary of phase B are connected in so that the arrow on the transformer runs concurrently with the arrow-head

on the choke-coil circuit. $E_b'E'$ is opposite in polarity to OE_a; therefore the 145 turns of the secondary on the A transformer are reversed, so that the arrow on the transformer is in opposition to the arrow-head on the choke-coil circuit.

In practice it is of course **impossible** to make a **choke-coil** which has no **resistance.** The plan to adopt is to work out by the above method the approximate size of choke-coil required. After a provisional design has been made out the approximate I^2R load caused by the coil can be calculated. This I^2R load is then added on to the unbalanced three-phase load giving a value to the resultant unbalanced load and a new value to $E' \sin(\omega t - \beta)$. We can then proceed to find the exact size of choke-coil by this method of trial and error.

EXAMPLE IV. **Vector diagram of synchronous motor.**

In the previous problems we have been concerned with vectors having a fixed phase relation to one another. In some problems, however, we are concerned with the variation of the phase angle and with the effect of the phase angle upon the amplitude of the quantities under consideration. A good example of this kind of problem is found in the study of the synchronous generator and motor.

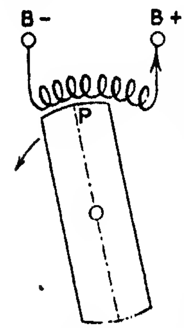


FIG. 102.

Fig. 102 represents the armature of a single-phase alternator connected to the supply mains. The arrow-head on the circuit denotes the direction taken as positive for the purpose of the vector diagram (Fig. 103). At the instant when the right-hand terminal is positive the busbar-voltage ON is opposed to the arrow-head. ON is therefore taken as negative in Fig. 103, while the voltage generated in the winding is taken as positive.

Let the terminal E.M.F. of a synchronous generator be represented by the vector OE_T, and let the current be almost in phase with the terminal E.M.F. and be represented by the vector OI. The reactive voltage drop in the armature winding will be at right angles to the current, and may be represented by E_TX; while the resistance drop is given by XE_g. The vector OE_g then gives the generated voltage. This is ahead of OE_T by the angle ζ. The armature current produces field distortion (see page 183), so that the phase of the generated voltage lags behind the phase position of the centre-line of the pole by an angle that we will denote by θ.

In Fig. 103 the line OP is the centre-line of the pole of a generator, which is supposed to be revolving in a counter-clockwise direction. The vector OE_g gives the generated voltage and the vector OE_T the

terminal voltage. Let $\theta+\zeta=\sigma$; then σ is the angle between the centre-line of the pole and the vector that represents the terminal voltage.

If the machine is operating as a motor, the current will be almost 180° out of phase with the terminal E.M.F. E_T, and may be represented by OI in Fig. 104. The impedance drop will now bring E_g to the right of E_T, and the field distortion will bring the centre-line of the pole OP still further to the right. The angle σ' between OE_T and OP is now of opposite sign to σ in Fig. 103.

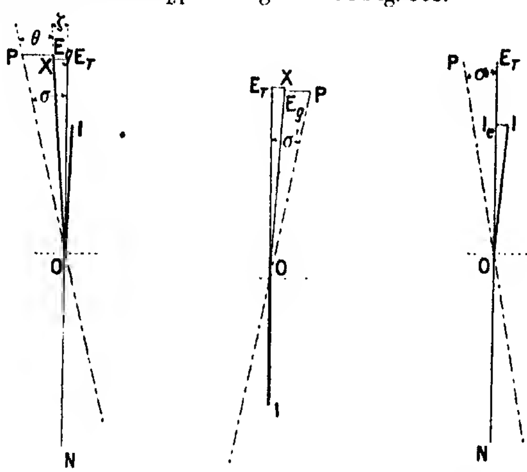


FIG. 103. FIG. 104. FIG. 105.

If the field magnet is excited so as to give a back E.M.F. almost equal to the busbar voltage, the armature current OI will be almost in phase with the terminal voltage. In Fig. 105 drop a perpendicular II_e from I on to OE_T. Then the product $I_e \times E_T$ gives us the power delivered by the generator. For small values of σ the current is proportional to σ. Let $I_e = I_u\sigma$, where I_u is a constant, the value of which is considered on page 176. Then the power is $E_T I_u \sigma$. The torque Q_g required to give this output is inversely proportional to the speed.

$$Q_g = \frac{E_T I_u \sigma}{9{\cdot}81 \times 2\pi \times R_{ps}} \text{ kilograms at a metre,}$$

where R_{ps} stands for the revolutions per second. Thus we see that the turning moment is proportional to the angle between the centre-line of the pole and the vector representing the terminal voltage. At no load σ is almost zero. As the load is increased σ is increased. In a machine of ordinary regulating qualities σ may be 0·27 of a radian (say 15°) at full load. On a two-pole machine

the displacement of OP in the clock diagram is the same as the mechanical angle of displacement of the field magnet on the machine; but on a multipolar machine having p pairs of poles the mechanical displacement u of the centre-line of the pole behind the vector representing the terminal voltage corresponds to an electrical angle $\sigma = pu$ on the clock diagram.

If the prime mover ceases to provide a forward turning moment, the centre-line of the pole (OP in Fig. 105) falls behind the phase of the terminal E.M.F., and the machine becomes a synchronous motor (see Fig. 106). The current OI is now nearly 180° out of phase with E_T. Projecting OI upon ON, we get OI_e, the component of the current that is directly out of phase with OE_T. The product $I_e \times E_T$ gives us the electrical input to the motor. As before, let $I_e = I_u\sigma$. The torque is now a forward torque tending to drive P forward to the synchronous position; it may be denoted by

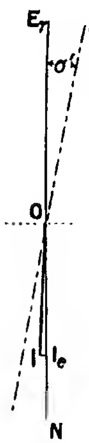


Fig. 106.

$$Q_s = \frac{E_T I_u \sigma'}{9{\cdot}81 \times 2\pi \times R_{ps}}.$$

Thus we see that the conditions controlling the flow of current through the armature are such that when P is displaced from the synchronous position E_T a turning moment comes into operation, which tends to move P towards E_T; and this turning moment or synchronizing torque is proportional to σ for small values of σ. The electrical forces operate upon the magnet in a manner analogous to the forces exerted by the spring upon the balance-wheel of a watch, in which the restoring force is proportional to the displacement. If the machine is running at no load and P is forcibly displaced from E_T and then released, it will swing back; and on reaching E_T it will swing past, just as a balance-wheel swings when it is displaced and released. This motion of P with respect to E_T is called '**phase-swinging.**' The natural period of this swing depends upon the constants considered on page 228. It must be remembered that the clock diagram is supposed to be revolving all the time with the same frequency as the machine. When the busbar voltage has a uniform frequency, E_T is supposed to be revolving with the same uniform frequency. If there is no phase-swinging, P will take up a definite position with respect to E_T, and will revolve at the same speed. If P is behind E_T the machine is acting as a motor yielding a torque proportional to σ'; if P is ahead of E_T, the machine is acting as a generator, and is being driven with a torque proportional to σ. If P swings backwards and forwards past E_T, the machine acts alternately as a generator and a motor.

Sometimes a synchronous motor yielding a certain mean turning moment that calls for a displacement σ' of the field-magnet P exhibits some phase-swinging; so that P, instead of maintaining the angle σ' constant, swings backwards and forwards between the limits P' and P'', as indicated in Fig. 107.

Consider two similar generators connected in parallel to the busbars $B+$ and $B-$, as shown in Fig. 108, and supplying a feeder circuit F, F'. In dealing with a case of this kind, in which there are several circuits in parallel, it is important to agree upon the convention as to positive and negative currents in each circuit before attempting to draw the clock diagram. A simple convention is that indicated by the arrow-heads in Fig. 108.

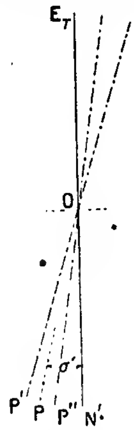


FIG. 107.

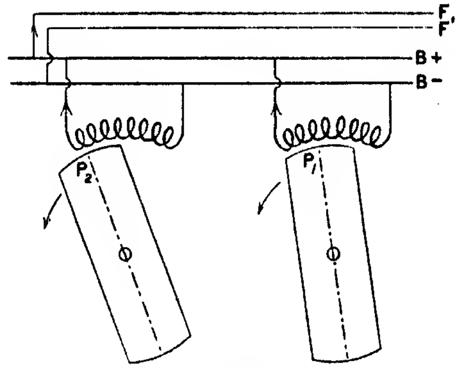


FIG. 108.

Here the busbar voltage is taken as positive when $B+$ is positive and $B-$ is negative. The direction of a positive current in each circuit is indicated by the arrow-heads. In the clock diagram, Fig. 109, ON is taken as representing the busbar pressure, and ON' as the back pressure of the generator. The phase positions of the centre-lines of machines 1 and 2 may then be represented by the vectors OP_1 and OP_2 respectively. As shown in Fig. 109, σ_2 is greater than σ_1, so that I_2 will be greater than I_1. The sum of the currents, I_1+I_2 is the current taken by the feeder. In phase and amount it depends upon the character of the load upon the feeder. The engine driving P_2 is exerting a greater turning moment than the engine driving P_1, and forces P_2 ahead of P_1, so as to take a greater share of the load. If there is no phase-swing, the angle between P_2 and P_1 will remain constant as long as the distribution of steam supplied to the two engines remains unaltered. The governors of engines are usually provided with a means ('speeder' gear) whereby

the steam supplied at a given speed can be varied at will. By means of this speeder gear the distribution of load between the two machines can be equalized as in Fig. 110, so long as there is no phase-swinging.

It is common to find a certain amount of phase-swinging between P_1 and P_2: that is to say, first P_1 gets ahead and I_1 increases, then P_2 gets ahead and I_2 increases, the sum of I_1 and I_2 remaining constant. This phenomenon will be most marked if the natural frequency of phase-swing of the generators is the same as the frequency of a periodic irregularity in the turning moment in one or both of the engines. The conditions under which this arises are considered on page 230.

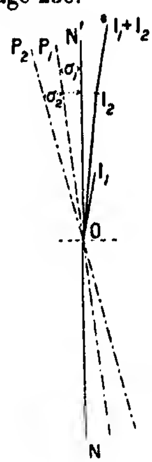


FIG. 109.

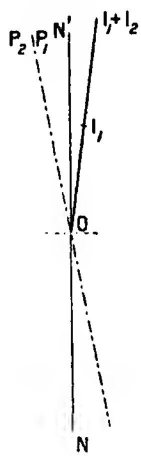


FIG. 110.

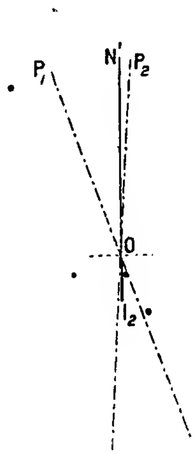


FIG. 111.

As the load on the feeder increases, the speed of the engines will be slightly decreased, and this causes the governors to supply more steam. The increased turning moment then forces P_1 and P_2 further ahead of ON', and a corresponding increase occurs in I_1 and I_2. Suppose that on machine No. 2 the steam is shut off; P_2 will fall behind ON', as shown in Fig. 111, until the negative σ_2' causes to flow a negative current I_2 sufficient to provide the turning moment required to drive the engine. Machine 2 is then running as a synchronous motor.

It will be seen that in Figs. 109, 110 and 111 we are concerned with the changing position of the vectors P_1 and P_2 and the effect of the change of position upon the currents in the circuits.

EXAMPLE V. **Locus diagrams.**

The study of the changes in the magnitude and position of vectors, such as P_1 and P_2, and the effect of these changes upon the currents in the circuits, is greatly aided by the use of locus diagrams,

The locus diagram of a synchronous generator or motor provided with salient poles is rather tedious to draw from design data of the machine, and indeed cannot be drawn so as to take into account with perfect accuracy all the factors that determine the performance in actual practice. But an approximate locus diagram, which in the main exhibits all the leading features in the performance of the machine in a manner that is sufficiently quantitative for many practical purposes, can be constructed with ease if we are allowed to assume that the machine possesses certain qualities that might be attributed to an ideal machine. For instance, the locus diagram is greatly simplified if we can assume that the reluctance of the magnetic circuit is the same for a cross-magnetizing M.M.F. as for a demagnetizing M.M.F. This is very nearly true in a turbo-generator having a cylindrical field-magnet, but is not in general true where the machine is provided with salient poles. Again, matters are much simplified if we can neglect the saturation of the magnetic circuit, and can assume that the inductance of the armature winding remains constant over the ranges of armature current within the purview of the locus diagram.

In connection with Fig. 103 we saw that the angle σ was made up of two angles, ζ and θ. ζ depends mainly upon the reactive voltage generated by the leakage field across the armature slots and around the armature end-windings, whereas θ depends upon the distortion of the flux across the face of the pole. If we are permitted to make the assumptions set out in the last paragraph, it is legitimate to take the whole magnetizing effect of the armature current (that is, the leakage flux both across the slots and around the end-windings, and the flux distortion), and consider the E.M.F. set up in the armature by it just as if it were an E.M.F. of self-induction. Denoting by X_a the apparent reactance of the armature, due to this total magnetizing effect, by R_a the resistance of the armature, and by E_F the E.M.F. generated by the undistorted flux set up by the field-winding, we see that the busbar voltage is balanced by the sum of three E.M.F.'s, namely:

$$I_aX_a, \quad I_aR_a. \quad \text{and} \quad E_F.$$

Fig. 112 shows how in a synchronous motor the terminal voltage OE_T (which is equal and opposite to the busbar voltage ON) is built up of $E_F = PE_T$, $I_aR_a = XP$, and $I_aX_a = OX$. In this figure E_F is taken smaller than E_T; that is to say, the synchronous motor is supposed to be under-excited. As a consequence, the current OI is lagging behind the busbar voltage by the angle ϕ. As the vertical component, OI_a, is 180° out of phase with OE_T, the machine is running as a motor. If the excitation of the field-magnet is kept constant while the load is changed, the point P must move on the arc of a circle P_1PP_2, having a constant radius E_TP and a centre at E_T.

While P moves on its circle, the point I must move * on the arc of a circle I_gIT, whose centre is at H. The line OH is drawn on the current scale equal to E_T/Z_a (where $Z_a = \sqrt{R_a^2 + X_a^2}$), and makes an angle ψ_s with the vertical line ON such that $\tan \phi_s = \frac{X_a}{R_a}$. Fig. 112 has been drawn to scale to represent the voltage and the current

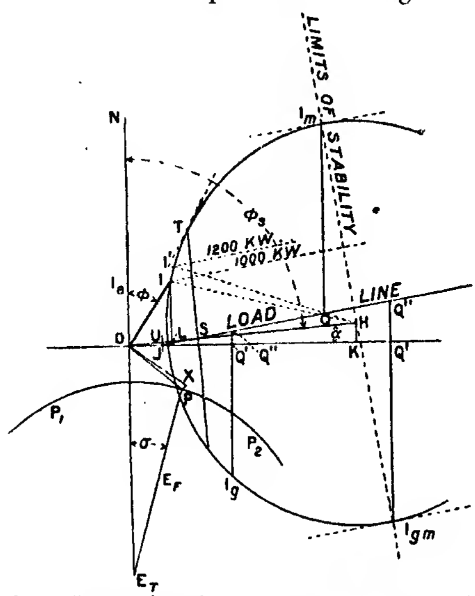


FIG. 112.—Locus diagram of synchronous motor or generator (under-excited). Scale: 1 cm. = 100 amperes; 1 cm. = 1000 volts.

per phase of a three-phase motor when running with the field-magnet under-excited. The following are the particulars of the motor in question:

> Output 1000 K.W.; voltage 6000 between terminals; 3470 volts from one terminal to the star-point; 40 cycles; 24 poles ($p=12$); 200 R.P.M. At an efficiency of 95 per cent. the full-load wattful current will be 102 amperes.

The value of c in equation (1) on page 228 is 224,000. From this we can calculate the value of I_u for normal excitation (to give 6000 volts no load):

$$Q_s = \frac{1 \cdot 73\ EI_u pa}{9 \cdot 81 \times 3 \cdot 33 \times 6 \cdot 28} = ca = 224{,}000a.$$

Therefore

$$\frac{1 \cdot 73 \times 6000 \times 12 \times I_u}{9 \cdot 81 \times 3 \cdot 33 \times 6 \cdot 28} = 224{,}000,$$

$$I_u = 370.$$

* See E. Arnold, *Die Wechselstromtechnik*, vol. 4, p. 417; also Dr. T. F. Wall, "The Theory of the Three-Phase Synchronous Machine," *Journal I.E.E.*, vol. 52, p. 277.

Full-load current $I_l = 102$; therefore $I_a = \frac{370}{101} I_l = 3{\cdot}64 I_l$.

$1/\sigma = 3{\cdot}64$; therefore σ at full-load $= 0{\cdot}275$ radian.

3470 volts $\times 0{\cdot}275 = 955$ volts $= I_l \times X_a$.

$$\frac{955}{102} = 9{\cdot}4 \text{ ohms reactance per phase} = X_a.$$

The resistance is 0.72 ohm per phase $= R_a$.

$$Z_a = \sqrt{0{\cdot}72^2 + 9{\cdot}4^2} = 9{\cdot}42 \text{ ohms per phase.}$$

Then $$\tan \phi_s = X_a / R_a = \frac{9{\cdot}4}{0{\cdot}72} = 13{\cdot}05.$$

In Fig. 112 the scales are 1 cm. = 100 amperes, and 1 cm. = 1000 volts. The vertical line ON represents the network pressure, 3470 volts to the star-point; OE_T is the terminal back voltage made up of OX (the reactive drop $I_a X_a$); XP (the resistance drop $I_a R_a$); and PE_T (the voltage E_F that would be generated by the field if it were undistorted). In this case the excitation of the field-magnet is taken as sufficient to give a terminal pressure of 5000 volts at no load, so that E_F represents to scale $5000 \div 1{\cdot}73 = 2880$ volts. The line OH representing 370 amperes is set off so that $\tan \phi_s = \frac{9{\cdot}4}{0{\cdot}72}$. The radius $HI = \frac{2880}{9{\cdot}42} = 306$ amperes. To set off the load line * we proceed as follows:

Draw a tangent from O to circle $I_g IT$ at T. Drop the perpendicular TS on OH. Bisect OS in U. Draw UJ parallel to TS, cutting OK in J. Join JS. Then JS produced is the load line. Any vertical line such as IL drawn from a point on the circle to the load line gives the wattful current, which, when multiplied by the voltage per phase and by 3, gives the output of the motor in watts. The intercept between the load line and OK gives the wattful current that supplies the ohmic loss in the armature. A point on the circle $I_g IT$ below the load line, such as I_g, gives the magnitude and position of an armature-current vector when the machine is running as a generator. As before, the intercept between the load line and OK gives the ohmic loss, and a perpendicular from I_g to OK gives the output at the terminals.

If we draw the line marked '1000 K.W.,' parallel to the load line and at a vertical distance from it to represent 100 amperes (the wattful current to give full load minus the $I^2 R$ loss), we cut the circle at I and obtain OI, the full-load current vector lagging by the angle ϕ behind ON, on account of the weak excitation of the field-magnet.

* For the proof of this construction and for further extensions of it, the reader is referred to the paper by Dr. Wall in the *Journal I.E.E.*, vol. 52, p. 281.

OX at right angles to OI represents, to the voltage scale, the reactive drop I_aX_a. The maximum load that the motor can give for the strength of the field-magnet, represented by E_TP, is found by drawing a tangent to the circle at I_m parallel to the load line. The line I_mQ represents 285 amperes. $\frac{285 \times 3470 \times 3}{1000} = 2970$ K.W., the maximum output of the motor for this excitation. Any load beyond this will cause it to break step. When the machine is running as a generator, the maximum output (measured at the terminals) is given by the current $I_{mg}Q'$. The maximum output measured internally is calculated from the current $I_{gm}Q''$.

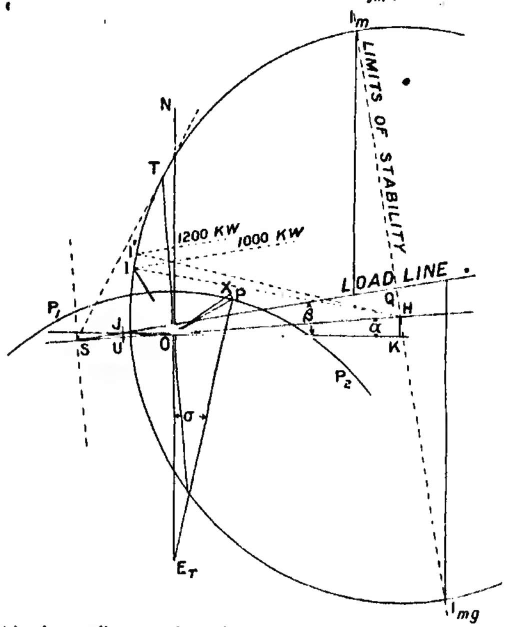


FIG. 113.—Locus diagram of synchronous motor or generator (over-excited). Scale: 1 cm. = 100 amperes; 1 cm. = 1000 volts.

When the synchronous motor is over-excited, the locus diagram takes the form shown in Fig. 113. The point H is obtained exactly as before; but as E_TP is now greater than E_TO, part of the circle P_1PP_2 lies above O, and by similarity part of the circle I_gIT lies to the left of O. As O is now inside the circle, the polar to the pole O is the dotted line through S. ST is a tangent to the circle, TO being at right angles to OH. U is midway between S and O, and UJ is parallel to OT. SJ gives the load line, which is inclined to OK by the angle β, such that $\beta = 2\alpha$. Tan $\alpha = \frac{R_a}{X_a}$. The full-load

point I is obtained as before, by drawing the dotted line marked '1000 K.W.' at a vertical height of 100 amperes above the load line and finding the point I where it cuts the circle.

Figs. 112 and 113 also give the point I' for the load of 1200 KW. It will be seen that the angle IHI' in Fig. 112 is greater than IHI' in Fig. 113 in about the same proportion as the radius HI in Fig. 113 is greater than HI in Fig. 112. Thus a small definite change in the value of the angle σ causes a greater change of load when the machine is highly excited than an equal change in the value of σ when the machine is not so highly excited. The value of I_0 is almost proportional to E_TP, which represents to scale the voltage that would be generated by the field-magnet if the machine were running at no load.

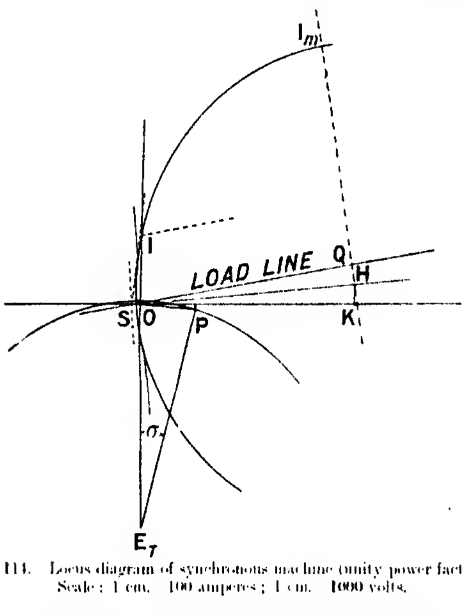


FIG. 114. Locus diagram of synchronous machine (unity power factor). Scale: 1 cm. = 100 amperes; 1 cm. = 1000 volts.

It is seen from Fig. 113 that the maximum load that the machine can take without breaking step is also almost proportional to E_TP.

Fig. 114 shows the locus diagram when the excitation is such as to give unity power factor on full load. Some of the lines of the diagram are nearly coincident, and hardly leave room for the insertion of the letters.

If it were desired to draw the V-curve giving the relation between the armature current and the field excitation for any given state of load it is more convenient to proceed by a diagram* like that given

* See Dr. Wall's paper quoted above.

in Fig. 115. If we were to employ the construction given in Figs. 112 and 113, it would be necessary to construct a new figure for each degree of excitation.

The method of constructing Fig. 115 is as follows: The vertical line from O is produced, and on it is taken a centre F whose distance from O is equal to $\frac{V}{2R_a}$, where V is the voltage per phase and R_a is the resistance of one phase of the armature. This distance must be set off to the current scale. For instance, for the machine in question we have $V=3470$ and $R_a=0{\cdot}72$. Therefore $V\div 2R_a=2410$ amperes; and as the scale employed is 1 cm. $=$ 100 amperes, the

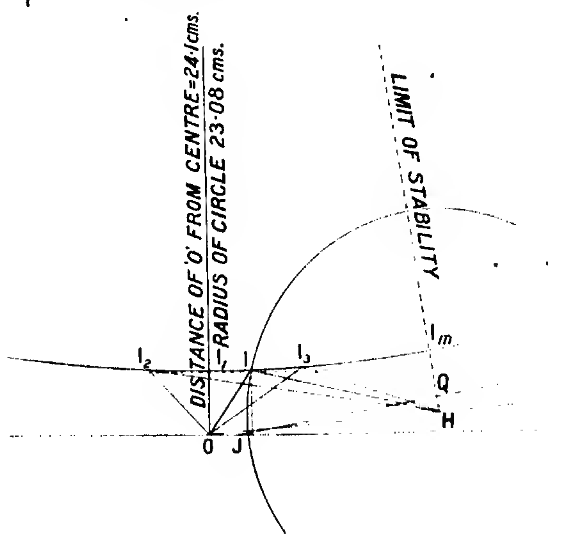


FIG. 115. – Locus diagram of synchronous motor on constant load. Scale: 1 cm. = 100 amperes; 1 cm. = 1000 volts.

centre point F will be 24·1 cms. above O (off the paper in this case). Next calculate the armature current that will flow at full load, unity power factor, allowing for all losses, including the armature I^2R losses. Take the friction and windage at 10 K.W., the iron loss at 25 K.W., and the copper loss at 22 K.W.

$$1000+10+25+22=1057$$

$$\frac{1057}{6000\times 1{\cdot}73}=102 \text{ amperes per phase.}$$

Set off $OI_1=1{\cdot}02$ cms. Take FI_1 as the radius of a circle whose centre is at F. In this case $FI_1=23{\cdot}08$ cms. This circle is the locus of all such points as I, I_1, I_2, I_3, etc., which mark the end of the radius vector representing the current taken at full load of

1000 KW. when the excitation is varied.* The dotted line shown in the figure is drawn at a distance of 0·994 cm. to represent the constant wattful current that supplies the load: 1000+10+25=1035 K.W. The vertical distance between the dotted line and the circle gives the current that represents the I^2R loss in the rotor. This last increases as the square of the radius vector OI; hence the curvature of the circle upon which I lies.

While the Figures 112, 113, 114 and 115 are useful in showing in a simple manner the general characteristics of the synchronous motor, they cannot be used for quantitative determination of the currents and power factors at different loads, because their construction is based upon the assumptions mentioned on page 175, and these assumptions lead us into considerable error when we are dealing with a salient-pole machine. In order to get more exact quantitative determinations, one must take into account the fact that the reluctance of the magnetic path for the cross-magnetizing flux is in general higher than the reluctance of the magnetic path for the main working flux. On a salient-pole machine the difference in the reluctance of these two paths has a great influence upon the position taken up by the field-magnet with respect to the vector that represents the terminal pressure.*

In order to plot the V-curve of a synchronous motor from no-load data or from particulars of design, the following information is required: (1) the no-load magnetization curve; (2) the short-circuit characteristic, or particulars of design from which it can be deduced; (3) the true reactance of the armature winding (that is, the reactance caused by flux that encircles the armature winding across the slot and around the end-windings); (4) the ratio of pole-arc to pole-pitch.

The procedure can be followed from the example worked out below. Fig. 116 gives the no-load magnetization and short-circuit characteristic of a 1000-KW., three-phase, 40-cycle synchronous motor. The true reactance of the armature may be taken at 2·36 ohms per phase; the resistance of the winding is 0·72 ohm per phase. The ratio of pole-arc to pole-pitch is 0·71. We may divide the ampere-turns on the field-magnet on short-circuit, when 102 amperes are flowing in the armature, into two parts. The total ampere-turns per pole are 2800. The reactance voltage is 240 per phase, or 416 volts in two phases at 120 degrees to one another. From the no-load magnetization curve we see that to generate 416 volts requires 260 ampere-turns per pole. Subtracting these from 2800, we get 2540 ampere-turns as the demagnetizing effect of the armature ampere-turns when running at 102 amperes on short-circuit. Thus we see that the armature ampere-turns can be calculated for any armature current by multiplying the amperes by 25. When the machine is

* See *Specification and Design of Dynamo-Electric Machinery*, p. 294.

running on a very low power factor, so that the armature magnetomotive force operates almost entirely as a magnetizing or demagnetizing effect, the point of greatest magnetomotive force being nearly opposite the centre of the pole, almost the whole of the 2500 ampere-turns are effective upon the main magnetic circuit. By 'main magnetic circuit' is meant the circuit that is embraced by the field coils, and which is made up of the air-gap under the poles, the pole limbs and yoke, and the armature core. When, on the other hand, the machine is running on a power factor near unity, so that the armature

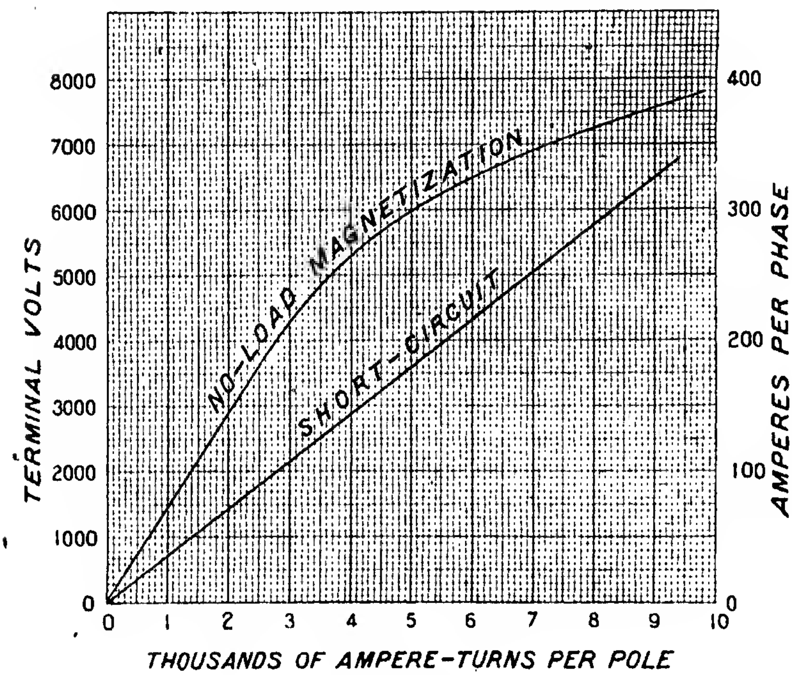


FIG. 116.

magnetomotive force operates almost entirely as a cross-magnetizing effect, the point of greatest magnetomotive force being nearly midway between two poles, the 2500 ampere-turns are expended upon a magnetic circuit comprising the air-space between the poles, which is of much higher reluctance than the main magnetic circuit. We may arrive at the resultant of the direct magnetizing effect and the cross-magnetizing effect at any particular power factor by resolving the total magnetomotive force of the armature into two components at right angles to one another: one operating on the main magnetic circuit and the other on the circuit of the cross

flux. It is then necessary to multiply the cross magnetomotive force by a coefficient K_q, to allow for the greater reluctance of the cross-circuit. The value of this coefficient depends upon the ratio of the pole-arc to the pole-pitch, and upon the shape of the pole. For salient poles having overhanging lips and bevels of normal dimensions, the value of K_q can be obtained from Fig. 117, in which the value of the coefficient is given for different ratios of pole-arc to pole-pitch. In our case the ratio of pole-arc to pole-pitch is 0·71, which gives $K_q = 0{\cdot}4$. That is to say, that the amount of cross flux produced by a given armature magnetomotive force at unity power factor is 0·4 of the direct flux which the same magnetomotive force could produce if operating directly upon the main magnetic circuit.

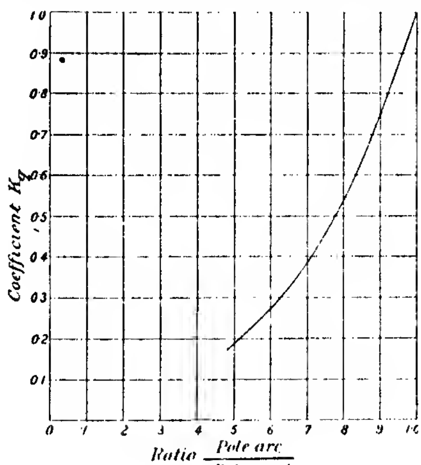


FIG. 117.

The values and phase positions of the armature current when the machine is running at full load and at various power factors can be taken directly from Fig. 115, and the construction for finding the ampere-turns per pole can be continued as shown in Figs. 118, 119 and 120. Fig. 118 deals with the case of the motor running at full load, unity power factor. The line OI_1 is taken from Fig. 115, and gives to scale 102 amperes in phase with the busbar voltage and 180° out of phase with the back pressure E_T, which in this figure is drawn to the scale: 1·73 cms. = 1000 volts. By our adopting this scale, the number of centimetres in OE_T and in the other voltage lines, multiplied by 1000, gives us the terminal voltage direct, to suit the ordinate scale in Fig. 116. The reactance voltage $E_TX = 416$ volts, and that absorbed in the resistance, XR, is

$$0{\cdot}72 \times 102 \times 1{\cdot}73 = 126 \text{ volts.}$$

Setting these out as in Fig. 118, we obtain the generated voltage, 5900. From Fig. 116 we see that this requires a resultant excitation of 4900 ampere-turns per pole. We therefore set off OF, 4·9 cms. long. At right angles to OI, we set off $OB = 2·54$ cms., to represent the 2540 ampere-turns per pole (see page 181). The cross-magnetization effect produced will be only 0·4 of this, so we mark off

$$OC = 0·4 \times 2·54 \text{ cms.},$$

and describe a circle* CDB having the diameter CB. Also upon OB as diameter describe the circle OAB. Join FC and produce

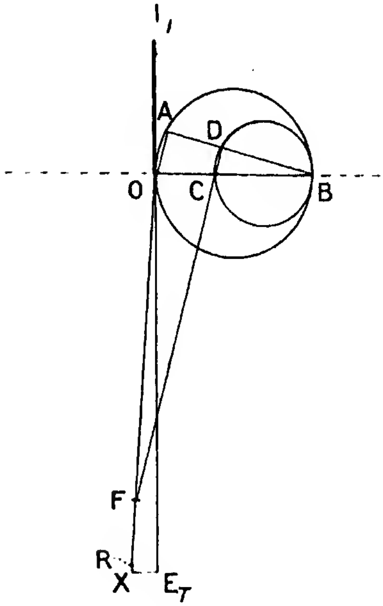


FIG. 118.

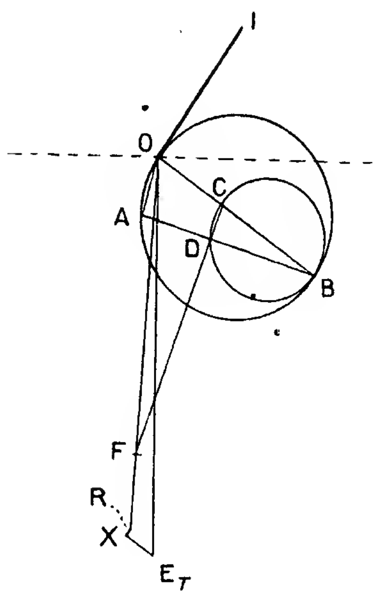


FIG. 119.

to D. Draw BDA. Join OA. Then OB is resolved into two components, OA and AB, one parallel to FD and the other at right angles to it. Further, the line AB is divided so that $AD : AB$ as $0·4 : 1$, so that AD represents the cross-magnetizing effect and OA the demagnetizing effect. If now we excite the field-magnet with a number of ampere-turns per pole represented by FD—in this case 5500—the resultant ampere-turns will be

$$FD + DA + AO = FO = 4900 \text{ ampere-turns per pole.}$$

A similar construction for the case where the machine is under-excited, and is taking the lagging current OI (Fig. 115), is shown

* See Dr. Wall, *Journ. I.E.E.*, vol. 52, p. 283.

in Fig. 119. Here the ampere-turns per pole are given by $FD = 3500$ ampere-turns per pole. The construction for a case in which the machine is over-excited and *is taking the leading current* OI_2 *(Fig. 115), is shown in Fig. 120. Here* $FD = 8150$ *ampere-turns per pole.*

By drawing several of these figures for various positions of OI, we can plot the full-load V curve * shown by the full line in Fig. 121.

If we had worked only from Fig. 115, and had taken such lines as HI as being proportional to the excitation of the field-magnet,

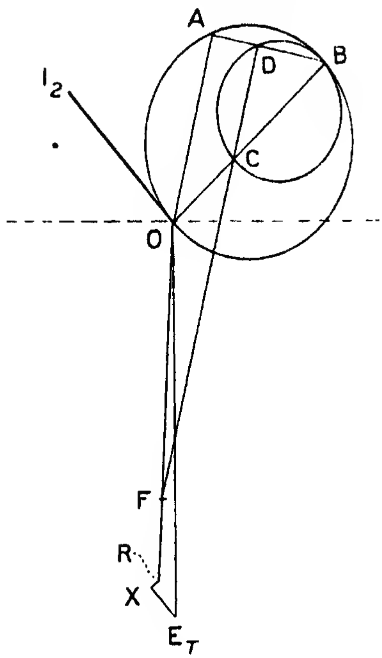


Fig. 120.

we should have obtained the V curve shown by the dotted curve B in Fig. 121. This curve differs very widely from the full-line curve A, for two reasons. It is based on the value of $X_a = 9{\cdot}4$ (see page 177), while this value of the synchronous reactance is only approximately right for power factors near unity. Further, it takes no account of the saturation of the iron, and the consequent rise in the resultant ampere-turns required as the generated voltage

* See Dr. Wall in paper quoted above, for close correspondence between a curve obtained on test and a curve obtained in this way when the right values are taken for armature reactance.

is increased beyond 6000, and the consequent fall in the resultant ampere-turns when the generated voltage falls below 6000. A dotted B curve could be obtained more nearly approaching curve A by choosing a higher value for X_a, to suit the cases of lower-power factor; but it is only by splitting up the armature reaction into its two components, and dealing with them in some such way as is shown in Figs. 118, 119 and 120, that one can expect to approximate the effects actually occurring on the running machine.

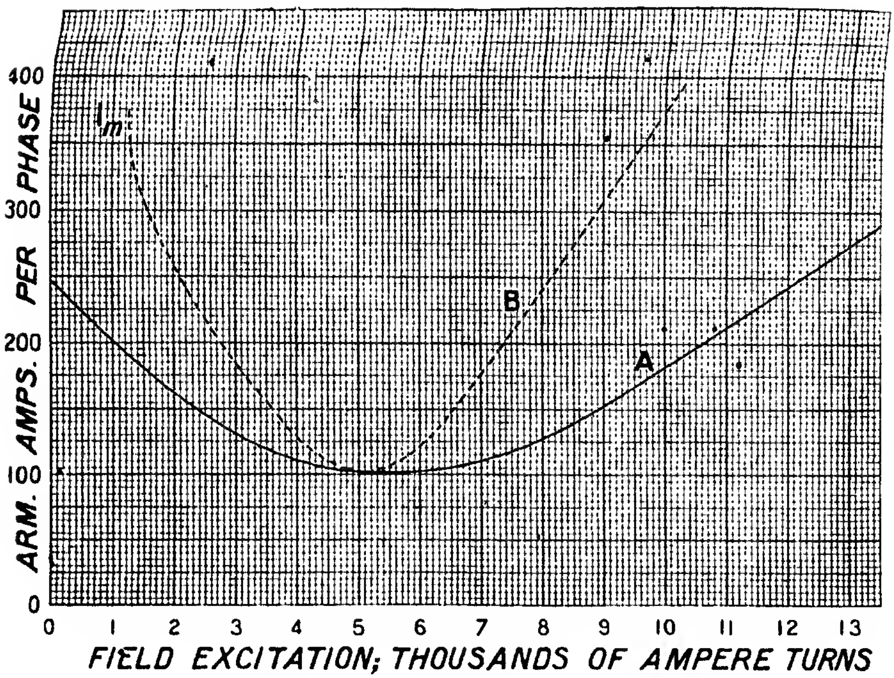


FIG. 121.

Heyland diagram of induction motor. This is another example of a locus diagram, which tells us at a glance how the value and position of the current vectors vary with the change of load. As the reluctance of the magnetic path for any orientation of the magnetic field is much more nearly constant on an induction motor than on a synchronous motor, the Heyland diagram enables us to make quantitative determinations with much greater accuracy than can be obtained in the case of the circle diagram of the synchronous motor. As the use of the Heyland diagram is already fully described in many text-books, it is unnecessary to reproduce it here.

CHAPTER VI.

ALTERNATING CURRENT GENERATORS.

Failure to generate electromotive force.

If an alternating current generator, supposed to be running under proper conditions, fails to generate electromotive force, one should in the first place see whether the field-magnet is properly excited. If the exciting current is supplied from independent continuous-current busbars, the field-magnet can be tested while it is stationary. Its magnetic state can be tested by bringing near to it a screw-driver or other suitable piece of magnetic metal large enough to be held firmly in the hand. One should never attempt to hold a screw-driver or other piece of magnetic metal near to a field-magnet while it is revolving. A loose piece of metal may make a sudden dart towards the poles and cause an accident. Should it appear that the field-magnet is not excited, one must test for a break in the continuity of the field circuit and for short circuit, as described on page 36. Many alternators are excited by means of an exciter directly connected to the shaft of the alternator, and the magnetizing current can only be generated when the alternator is running. In this case one must rely upon the ammeter in order to ascertain whether the current is flowing and whether it is of the right value, having regard to the position of the rheostat. The field circuit should be thoroughly overhauled when stationary, and tested for open circuits and short circuits. If neither of these defects is present, the current through the winding must necessarily magnetize the poles; but it is just possible that the failure to generate volts may be due to the reversed polarity of some of the poles. For instance, a very large slow-speed alternator might have its wire-wound field-magnets arranged so as to be connected with two sets of poles in parallel. If the connections to one of these sets were reversed, the magnetization of the poles would result in such a distribution of electromotive force in the armature as to give no resultant voltage at the terminals. Methods of checking the polarity of the poles are considered on page 191.

Assuming that the field-magnet is all in order, we can proceed to check the voltmeter circuit and the armature. It may be that the voltmeter is disconnected either on account of the absence of fuses (which are commonly provided to protect the voltmeter transformer) or on account of some break in the circuit. Where two voltmeters are provided on the switchboard, it may be convenient to plug in a second voltmeter to check the first one. The voltmeter circuit having been looked to and the voltmeter itself found to be in working order, we may proceed to make a closer examination of the armature circuits. These should be checked for open circuit and

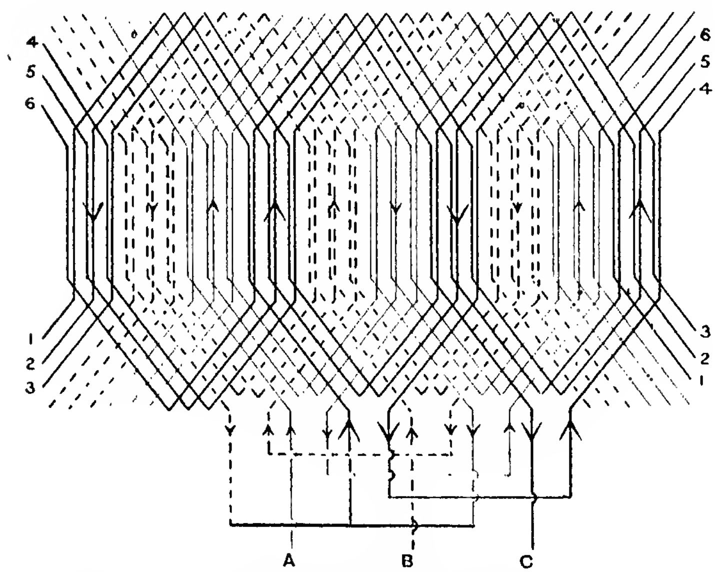


FIG. 200. Three-phase armature winding having two bars per slot. The two halves of the winding are connected in series so that the arrow-heads are concurrent.

short circuit by the methods described on pages 33 and 36. When the poles of the magnet are properly excited and rotated so that their lines of force cut across the conductors of the armature, an electromotive force must necessarily be generated in each individual coil. It is, however, possible that the armature coils may be so connected up that all the electromotive forces balance and give a resultant equal to zero. Such a case might arise where an armature is wound with two circuits intended to be connected in series, as shown in Fig. 200, which by some mistake are connected as shown in Fig. 201.

In some polyphase armatures wound with re-entrant windings, it is possible to find certain points that are always at the same

potential. If by any accident these points were brought out to terminals, instead of the points that are widest apart in potential, the result would be to give us a machine which would generate no electromotive force.

It is generally possible to ascertain whether an electromotive force is being generated in one of the individual coils of a machine by pricking through the insulation with the sharp points of the apparatus shown in Fig. 9, and putting a voltmeter in circuit. In trying this experiment on a high-voltage generator, care must be taken not to get a shock from the high-voltage leads. It is best to

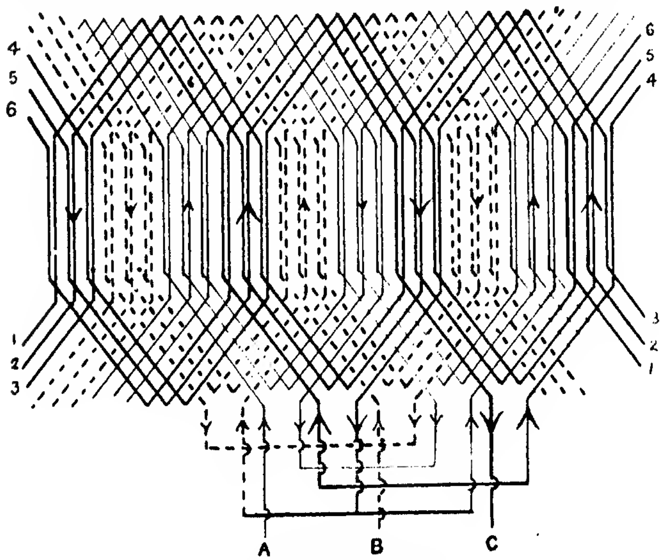


FIG. 201.—Three-phase armature winding as in Fig. 200, but with the two halves improperly connected.

test a coil near the star-point if that point can be earthed, or near to one of the terminals if the arrangements are such as to permit that terminal to be earthed. The connections to the voltmeter should be made in a substantial manner while the generator is stationary. If the individual coil yields electromotive force while there is no electromotive force at the terminals, the best plan is to obtain a diagram of the winding as it was intended to be made, and check it over coil by coil until the error is discovered.

An interesting case was brought to the attention of the author in America. Two generators were supplied to the same power-station to be driven by engines running at different speeds. One engine ran at 360 R.P.M. and the other at 400 R.P.M. For convenience

of manufacture, the generators were both built upon frames of the same size and were similar in every respect, except that one had 20 poles and the other 18 poles. When the machines were connected to the bus bars and run up to speed, it was found that neither would generate any voltage, although the field-magnets were excited and the armature windings appeared to be in perfect order. The mystery remained unsolved until it was discovered that the 18-pole field-magnet had been put into the 20-pole armature, and the 20-pole field-magnet into the 18-pole armature.

Failure to generate sufficient E.M.F. at no-load.

If an A.C. generator, running at the right speed and excited with normal field current, fails to generate sufficient E.M.F., it is a good

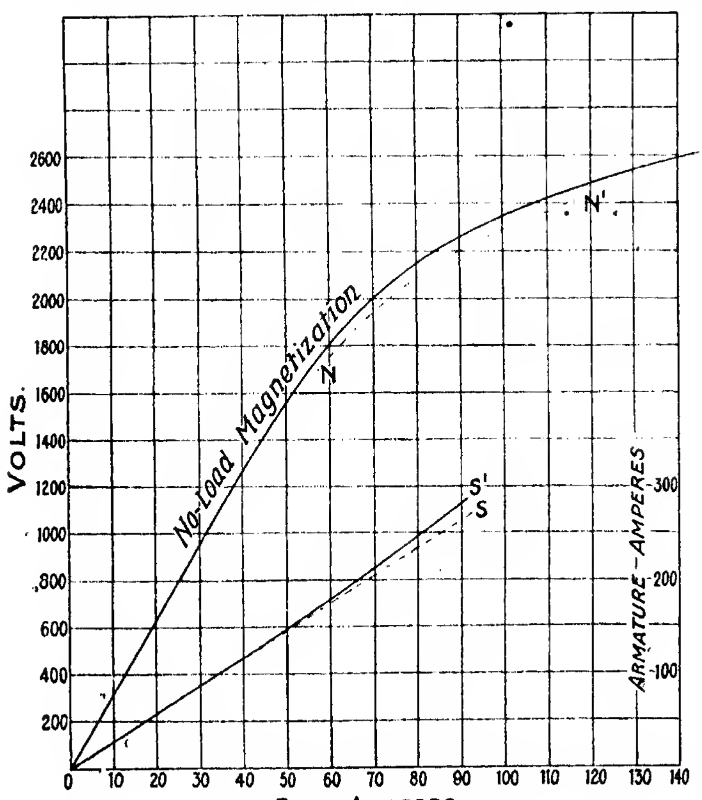


FIG. 202.—No-load magnetization and short-circuit characteristics of an A.C. generator.

plan to plot the no-load magnetization curve and examine its shape.

In taking the no-load magnetization curve, an ammeter is placed in the field circuit and a voltmeter (with its transformer when necessary) in the armature circuit. The machine is run at its rated speed, and the generated volts are observed for various field currents, beginning with small values and going up to 60 per cent. above normal field current. These values, when plotted, should give a curve having the general shape of the magnetization curve given in Fig. 202. Normal voltage is generally represented by a point on the curve a little above the knee.

If the voltage generated is only about half of what is expected, it may be that two parts of the winding, which are intended to be in series, are connected in parallel, or it may be that a winding intended to be connected in star has been connected in mesh, giving only 57·7 per cent. of its rated voltage. These are matters that are easily checked.

It may be that the voltage is not quite up to the rated voltage, though much more than one half of it. This may be due to any one of the following causes: (i) Some of the field coils are reversed; (ii) some of the field coils are short-circuited; (iii) some of the armature coils are reversed, short-circuited or cut out; (iv) the iron of the magnetic circuit is unduly saturated; (v) the field ammeter is incorrect; (vi) the voltmeter or the ratio of transformation of the transformer is incorrect; (vii) some mistake has been made in the measurement of the speed.

Polarity of poles. After satisfying ourselves that all the instruments are correct, the polarity of the field coils should be checked. This can be done by passing a current through the field circuit while it is stationary, and placing a short iron bar as shown in Fig. 203 from pole to pole. The amount of force taken to pull the bar away (from the poles) should be noted at each pair of poles. If any one of the field coils is reversed, there will be two North poles or two South poles together, and their attraction upon the iron bar will be very much reduced. A compass needle may also be employed in checking the polarity of the poles, but very great care must be exercised not to bring it too near to the poles or the polarity of the needle itself may become reversed.

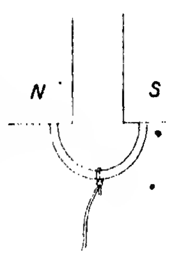


FIG. 203.

If it is desired not only to check the polarity of the poles but to measure the difference of magnetic potential between consecutive poles, a very satisfactory piece of apparatus is that proposed by Prof. A. P. Chattock.* It may be called a magneto-potentiometer. It consists of a helix of cotton-covered copper wire wound over a

* *Phil. Mag.*, vol. 24, p. 94 (1887): and see *Journal of the Institution of Electrical Engineers*, vol. 54, p. 43.

flexible core of non-magnetic material. The core can conveniently be made of four thicknesses of 0·1 centimetre fuller board (untreated), say 2 cms. wide and 30 cms. long. These form a core, which is sufficiently flexible after it has been wound over completely with No. 32 cotton-covered wire. A tape should be carried along the side of the core and looped back over the turns of wire at each end to prevent the turns from spreading. The ends of the wires should be connected by means of twisted flexible leads to the terminals of a flux-meter (see Fig. 204). For delicate measurements where the flux-meter is found not sufficiently sensitive it may be replaced by a ballistic galvanometer.

FIG. 204.—Flux-meter connected to Magneto-potentiometer.

If it is required to measure the difference of magnetic potential of two points not more than 10 inches apart, the flexible helix of wire is bent until the ends are at a distance apart equal to the distance between the two points in question. The ends of the helix are put as nearly as possible on the points A and B in Fig. 205, the difference of potential between which it is desired to measure. The flux-meter is then set at zero. The helix is then drawn quickly away to a position where there is no appreciable magnetic field, and the two ends are so placed that the line joining them is at right angles to the direction of any slight field that may exist. The deflection of the flux-meter is then proportional to the difference of magnetic potential between the two points A and B.

The instrument is most easily calibrated by straightening out the helix to its full length and placing it wholly inside a long solenoid wound with a known number of turns per centimetre of its length. When a current is passed through the solenoid, the difference in magnetic potential between the ends will be $1{\cdot}257\, I \times S \times l$, where S is the number of turns per centimetre in the long solenoid, and l *is the length in centimetres of the magneto-potentiometer helix parallel* to the axis of the solenoid. When the current I is *reversed*, let the deflection of the flux-meter be D_f; then one scale division of the flux-meter corresponds to a difference of magnetic potential of $2{\cdot}514 ISl/D_f$. Or if we prefer to measure potential difference in ampere-turns, one scale division corresponds to $2ISl/D_f$ ampere-turns. It is convenient to insert resistance in circuit with the flux-meter or ballistic galvanometer until the deflections read directly in ampere-turns.

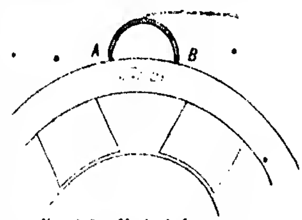


FIG. 205. Method of measuring the difference of magnetic potential between two points.

EXAMPLE. Let the flux-meter be adjusted by the insertion of resistance so that one scale division corresponds to 100 ampere-turns. Bend the helix into a horse-shoe shape so that its ends can be brought close up against the flanks of two pole pieces near the air-gap of an alternator, one being against a North pole and the other against a South pole. Let each of the poles of the alternator be excited to 5000 ampere-turns per pole, and let the flux-meter be brought to zero. Suddenly withdraw the helix and lay it down at a point where the magnetic field is negligibly small. Let the throw of the flux-meter be 90 scale divisions. Then the magnetic potential between the two points at which the ends of the helix rested is 9000 ampere-turns, showing that about 1000 ampere-turns are absorbed in the two pole shanks and the yoke. If the ends of the helix do not come quite against the flanks of the poles, there will be a reduction in the deflection corresponding to the drop in magnetic potential between the iron of the poles and the ends of the helix. Where this is small, it can be approximately calculated, and an allowance made for it.

If an apparatus of this kind is kept in readiness, properly calibrated, it can be used conveniently to measure the drop in magnetic potential between each pair of poles, and it will reveal a weakness in any pair of the poles whether due to deficiency in the number of ampere-turns or to undue reluctance * of part of the magnetic circuit.

If there is a blow-hole in a cast-steel yoke, which causes undue saturation of the steel and a serious drop in magnetic potential, the amount of the drop can be approximately measured by bringing the two ends of the helix up against the steel at opposite sides of the blow-hole (see Fig. 205).

* See pages 213 and 200 as to the possibility of changing the length of the air-gap.

Short-circuit of field coils. The test for short-circuit may be carried out as described on page 34. Sometimes a revolving field coil will be short-circuited or partially short-circuited when running, but not short-circuited when stationary. To check this, the resistance of the whole field circuit should be very carefully measured *when the machine is stationary, and again measured when the machine is running and before it has time to change its temperature.* If it is found that the total resistance is normal when stationary and has a lower value when running, there is an indication of a short-circuit, probably brought about by a movement of the coil due to centrifugal force. One way of finding the position of the short circuit is to pass a heavy field current for several hours while the field-magnet is revolving, and then to stop the machine as quickly as possible and feel the coils by hand. It may be possible to notice that a short-circuited field coil is slightly cooler than the others. If, however, the short-circuit occurs only in part of a coil, say in an inside layer, it will not be possible to notice the resulting slight difference of temperature by merely feeling the coil by hand. It may, however, be possible to notice a slight change in the resistance of the individual coils, if a very constant current of small value is passed through all coils in series and the voltage drops in the successive coils are measured on a milli-voltmeter. In this case the drop in voltage is used as a measure of the mean temperature on the assumption that the coil is not short-circuited when the machine is stationary.

Armature coils reversed. If a drawing of the armature winding is available, it will be possible to check the connections and direction of winding of each individual armature coil. Very frequently no drawing of the armature winding is available, and the investigator is thrown upon his knowledge of windings in finding out where the fault is. In order to check the correctness of the winding it is necessary in the first place to note very carefully the class into which the winding falls.* Whatever the number of phases of a machine, it is best to take each phase separately and deal with it as with a single-phase winding. For this purpose a few coloured chalks will be of service—different colours being used for different phases. Bar round the field-magnet until the middle of the poles is opposite the middle of the phase bands that are about to be checked. Mark the poles *N* and *S* alternately all the way round with conspicuous letters. Begin at the terminal of the phase that is being checked, and imagine a current flowing into the winding at that point. Let us say that this is opposite a North pole. Trace through the winding as far as possible by examination of the end-connections, and see that opposite all North poles the current is going inwards. It is best

* See *Specification and Design of Dynamo Electric Machines*, p. 87.

to indicate this with an arrow-head marked on the straight part of the projecting ends of the armature coils. Opposite the South poles the current ought to be coming outwards, and it may be indicated in the same way with arrow-heads on the winding. Sometimes, owing to the way in which the wires are taped up, it is impossible to tell by external examination which way a wire passes around the coil. In these cases a continuous current may be passed through the armature winding and the direction of flow of current determined by means of a compass needle. Thus the direction of winding of each phase of the armature may be checked. The plan of passing a continuous current through the armature and holding a compass needle near each armature coil in succession will also indicate which, if any, of the armature coils are cut out.

Low voltage on load.

Apart from defective regulation (as to which see page 207), it sometimes happens that a generator which yields its correct voltage at no-load will not yield its full voltage when loaded, even when the rheostat is entirely cut out and the speed brought up to normal value. This may be due to any one of the following reasons:

(1) The power factor of the load may be lower than the power factor for which the machine was designed.
(2) The exciting voltage may be too low.
(3) The resistance of the field-winding may be too high.
(4) Some of the defects mentioned on pages 191 to 194 may cause the voltage to be lower than it otherwise would be at no-load; but it is not until the generator is placed on load that the defect becomes noticeable.
(5) The magnetic leakage between poles on load may cause excessive saturation of the pole-shanks; so that the magnetization curve on full load tends to become horizontal for high values of the exciting current.

The methods of ascertaining which of these defects is causing the trouble are sufficiently obvious, and have for the most part been already dealt with in this chapter. If the power factor of the load cannot be improved, it may be possible to reduce the air-gap of the generator by one of the methods described on page 290.

The resistance of the field coils is sometimes too high, owing to the temperature rise being greater than was anticipated. If the temperature is well within a safe limit, the simplest cure is to increase the voltage of the exciter. This may be done by adding a few series turns to the exciter field poles. Sometimes these coils can be neatly wound over the shunt coils by the use of well-insulated flexible cable. Before this expedient is resorted to, it should be definitely ascertained

that the exciter voltage is not unduly low, owing to some of the defects mentioned on page 290.

Voltage too high.

If, after checking the voltmeter, the transformer ratio, the field ammeter, and the speed-counter, it appears that the voltage of the generator is too great, it is well to take a no-load magnetization curve as described on page 191. It may be that the voltage generated is about twice as high as it ought to be, owing to there being two parts of the winding in series which are intended to be in parallel; or it may be that a winding intended to be connected in mesh has been connected in star. Apart from accidents of this kind, it is very rarely that a machine generates much more than its rated voltage.

Unsteady voltage.

It sometimes happens that the voltage of an A.C. generator is so unsteady that incandescent lamps fed from it change their candle-power from moment to moment. If the undue flickering of the lights occurs at instants when the load is changing, it may be due to the poor regulating quality of the generator (see page 207). Flickering of lights sometimes occurs on machines of very good regulating qualities owing to the instability of the exciter. As explained on page 244, when a D.C. generator is running at a voltage below the knee of the magnetization curve, the voltage is very unstable, so that small changes of speed (such as might occur through the operation of the governor) or small accidental movements of the brushes on the commutator may bring about fluctuations in the exciting voltage and lead to flickering of the lights. The stability of an exciter can often be improved by the simple expedient of rocking the brushes forward; because with the brushes forward there is a demagnetizing effect on the field (see page 252), and it is necessary to increase the field current to get the desired voltage. This increases the leakage and gives further stability to the exciter. Where the instability of the exciter is too great to be cured in this way, it may be possible to add a rheostat or a permanent resistance in circuit with the main field current. This raises the exciting voltage and gives stability, but it reduces the efficiency of the plant. The best cure is to add stability plates to the field-magnets of the exciter, as described on page 293. Another possible cause of flickering of lights or unsteadiness in the generated voltage is a loose contact either in main field circuit or in the field circuit of the exciter. These circuits should be carefully tested and all contacts tightened up. There may be an intermittent break in the field-winding: for the method of dealing with this see page 36.

Unbalanced phases.

On page 162 are set out the conditions that must obtain in order that the phases of a polyphase system shall be balanced. A want of balance may be due either to a defect in the generator or to a defect in the method of loading it. With defects in the load we are not concerned here. If at no-load the voltages between terminals are balanced as to both magnitude and phase (see page 163), and it is found that on load the currents are unbalanced, there is evidence that it is the nature of the load that is at fault. This can be confirmed by measuring the voltage on each phase while the load current is flowing. If it is the nature of the load that is causing the trouble, we shall find that the voltage drop is greatest on those phases which are taking the greatest wattless current. If it is the generator that is at fault, then the phase that is yielding the greatest current will have the greatest voltage.

A dissymmetry in the winding may occur in the original design or by mistake in manufacture, or it may be caused by an accidental cutting out of part of the winding. The accidents of short circuit and open circuit are dealt with in Chapter I. A measurement of the resistance per phase and a comparison with the original test data, or a measurement of the insulation resistance, will usually reveal the existence of a defect if it has occurred since the machine was completed.

Let us assume that no accident has happened to the winding, and yet it shows dissymmetry between the phase voltages when the generator is run at no-load. The first step is to find out the nature of the dissymmetry. If the generator is a star-connected three-phase machine, the voltage of each phase should be measured to the star-point. Any inequality must be noted, the defective winding traced through slot by slot, and the connections compared with a diagram of the winding if one is available. In doing this it is well to use coloured chalk to mark the coils of each phase as they are traced out, arrow-heads being used to indicate the way a current would pass on its way to a terminal. When the tracing out is completed, the relation of the phases to one another is clearly exhibited by means of the colours and arrow-heads. If no diagram is available the "throw" of coils must be noted and the connections between coils checked to see that the polarity of all the coils is correct. On coil-wound machines it is very easy for a coil to be connected in the wrong way; so that its electromotive force is subtracted from that of the others instead of being added.

The electromotive forces measured to the star-point may all be equal, and yet the terminal pressures may be unequal. If this is found to be the case it shows that the phase displacement of the star voltages is not correct. This may be due to some of the coils being in the wrong slots.

If the generator is mesh-connected the mesh should be opened at the corners and each part of the winding tested separately. A good way of checking the phase displacement of the separate phases is to connect them temporarily in star. In doing this one may adopt the following plan. Go round the mesh, say clockwise, and mark the ends plus and minus so that the end of a phase by which we enter is plus. Then connect all minus ends to a star-point, and bring out the plus ends to terminals. If the phase of the voltage generated in each limb is correct, the voltage between terminals will be balanced. The nature of any departure from symmetry can be studied by drawing the vector diagram in which the voltages as measured are set off to scale.

On ordinary three-phase generators in which the number of slots per pole is divisible by three, it is very rarely that a mistake is made in the winding which leads to a dissymmetry. It is on wave-wound machines having a number of slots per pole which is fractional or not divisible by three, that mistakes are more likely to be made.

The complete consideration of the rules for obtaining symmetrical polyphase windings, with various numbers of slots and poles, is more within the province of a book on design than of this book. All that will be attempted here is a description of a ready method of ascertaining the amount of departure from symmetry that may be expected in any winding that does not conform strictly to recognized rules. The relations between the number of slots and number of poles that give the possibility of a perfectly symmetrical winding of a given number of phases is fully dealt with by Dr. S. P. Smith in his paper on "Theory of Armature Windings."*

* *Jour. Inst. Elec. Engineers*, vol. 55, p. 18 (1916). See also Whittaker's *Electrical Pocket Book*.

Let the total number of slots be denoted by S, the number of pole-pairs by p, and the highest common factor of S and p by F. Let

$$\frac{S}{F}=S' \text{ and } \frac{p}{F}=p'.$$

Let ψ be the mean angular phase displacement between the pressures induced in successive coils in the winding.

The condition necessary for the existence of a symmetrical winding is that the sum of the electromotive forces in all coils connected so as to form a closed mesh shall be zero. This condition is fulfilled if $S'\psi=2\pi$ radians.

In order that such a winding shall be a symmetrical N-phase winding we must fulfil the further condition that S' shall be exactly divisible by N.

We then get N equal phases displaced from one another by the angle

$$S'\psi/N=2\pi/N=\beta.$$

Further, if $p'=nN\pm 1$, where $n=0$, 1, 2 or 3, etc., then

$$p'\beta=(nN\pm 1)2\pi/N=\pm 2\pi/N=\pm\beta.$$

That is to say the same positions are obtainable in the field for N phases with p' pole-pairs as with one pole-pair. This is not possible if p' is a multiple of N, for when $p'=nN$,

$$p'\beta=nN(2\pi/N)=0.$$

The same result can be deduced from the fact that S' and p' by definition have no

By referring to Dr. Smith's formulae and tables we can see at once whether a strictly symmetrical winding is possible under the prescribed conditions, and in cases where it is possible we can check over the winding under investigation and see whether it complies with the rules laid down.

Most commonly there are an integral number of slots per pole-pair. If this number is not divisible by 3, it is not possible to make a three-phase winding which will comply with the strict rules. Nevertheless, it is often possible to make a winding which is so nearly symmetrical as to be perfectly good for all practical purposes.

Unsymmetrical windings which depart from symmetry by a negligible amount. One not uncommonly meets with a winding of this kind in practice,* and it may be necessary to check it over and ascertain the extent of the departure from symmetry.

A good method of doing this is to lay out a diagram like that given in Fig. 206. Each horizontal line on the diagram represents

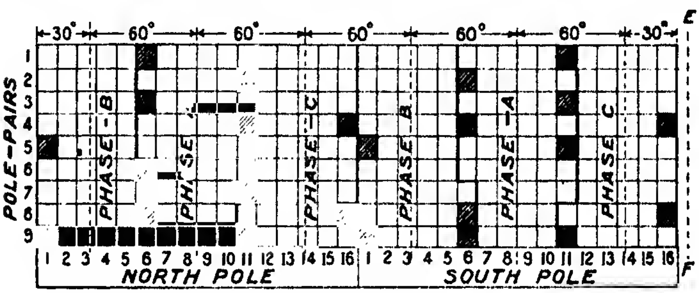


FIG. 206.—Method of laying out a three-phase armature winding lying in 16 slots per pole (18 poles), in order to ascertain the amount of deviation from perfect balance. The shaded squares represent empty slots.

the lay-out of the slots opposite one pole-pair. In Fig. 208 there are 16 slots per pole (32 per pole-pair, a number not divisible by three). The successive lines show the arrangements of phases in front of successive pole-pairs. The hatched squares indicate slots which are left vacant, and the thick lines divide the slots belonging to one phase from those belonging to another. Thus, of the 16 slots

common factor greater than unity, and since S^1/N is to be an integer, it follows that p'/N cannot be an integer. The permissible numbers of slots and coil-sides per slot in Lap and Wave double-layer windings to obtain 3, 4 or 6 symmetrical phases with various numbers of pole-pairs havo been worked out by Dr. S. P. Smith, and given in tables in his paper.

In cases where there are an integral number of slots per pole-pair, F equals p; so that $p' = 1$. In these cases the number of slots per pair of poles ($= S'$) must be divisible by N. Where F is greater than one its value gives us the number of circuits of exactly the samo electromotive force and phase that occur in the winding. These circuits may be connected either in series or in parallel.

* See *Specification and Design of Dynamo-Electric Machinery*, pp. 106, 107.

opposite the North pole of the first pole-pair, 1, 2, 3, 4 and 5 belong to phase $-B$. Number 6 is empty. Numbers 7, 8, 9, 10 and 11 belong to phase A, and 12, 13, 14, 15 and 16 belong to phase $-C$. Of the 16 slots opposite the South pole of the 8th pole-pair, numbers 1, 2, 3, 4 and 5 belong to phase B, number 6 is empty, numbers 7, 8, 9 and 10 belong to phase $-A$, and numbers 11, 12, 13, 14 and 15 belong to phase C, while number 16 is empty; and so on. It is required to know whether the phases are balanced, and if not balanced what is the maximum deviation from symmetry.

Method of moments. The shortest method, and one which is sufficiently accurate for practical purposes, is one based on the assumption that the sines of small angles are proportional to the angles, and that the ratio between the cosines of two nearly equal small angles is equal to unity. A more accurate method is given on page 201, but it need only be resorted to in special cases. The simple method is to regard all the wound slots of any one phase as equal weights distributed as shown by the white squares in Fig. 206, and to find the centre of gravity of these weights. If this falls upon the dotted line which represents the correct position for the centre of the phase in question, then the angle of displacement between the phases is correct. It should be noted in the first place that all phases have the same number of conductors, and that the great bulk of the conductors of each phase lie near the correct position for the centre of the phase (shown by the dotted lines). The differences between the arrangements of conductors of different phases are confined to comparatively few conductors on the outskirts of the phase-bands, and these ragged outskirts have a width of only about one slot pitch. These conditions are necessary if the sine and cosine assumptions mentioned above are to be approximately true.

To find the centre of gravity of any phase, say phase C, take moments about any line, such as EF. EF is in this case taken through the centre of a slot space immediately to the right of slot 16. We then have

$$\begin{array}{rcrcr}
7 & \times & 1 & = & 7 \\
9 & \times & 2 & = & 18 \\
9 & \times & 3 & = & 27 \\
9 & \times & 4 & = & 36 \\
9 & \times & 5 & = & 45 \\
1 & \times & 6 & = & 6 \\
\hline
44 & & & & 139
\end{array} \qquad \frac{139}{44} = 3{\cdot}1591.$$

Now the correct position for the centre of phase C is $3\frac{1}{6}$ slot-pitches away from the line EF. This is arrived at as follows: The correct position for the centre of phase $-A$ is mid-way between

slots 8 and 9. Each slot-pitch occupies $\frac{180}{16}$ degrees. Therefore 60° is represented by $\frac{60 \times 16}{180} = 5\frac{1}{3}$ slot-pitches. Therefore the dotted line through phase C should be one-sixth of a slot-pitch to the left of the centre line of slot 14. The difference between 0·1666 and 0·1591 is 0·0075. The phase displacement worked out in this way comes to $\frac{180}{16} \times 0{\cdot}0075 = 0{\cdot}084°$. The displacement of phase B is 0·084° in the opposite direction.

If we may assume a sine-wave field-form we can calculate exactly the deviation from symmetry. Assigning to each slot its phase angle θ, that is to say the angle between it and the correct centre of the phase-band, and taking the sines and cosines of these angles, we can make an exact summation of all the electromotive forces in quadrature and all the electromotive forces in phase. The method of working will be seen from the example given below.

Taking first phase C:

Slot No.	Angle θ in degrees.	$\sin\theta$	Number of Conductors.	Product.	$\cos\theta$	Number of Conductors.	Product.
11	− 31·875	− ·5280	× 1	0·528	·8192	× 1	0·8192
12	− 20·625	− ·3522	× 9	3·170	·9359	× 9	8·4181
13	− 9·375	− ·1629	× 9	− 1·466	·9866	× 9	8·8794
14	+ 1·875	+ ·0327	× 9	+ 0·294	·9995	× 9	8·9955
15	+ 13·125	+ ·2267	× 9	+ 2·041	·9740	× 9	8·7660
16	+ 21·375	+ ·1127	× 7	+ 2·887	·9109	× 7	6·3763
				+ 0·058			42·2845

Then the angle of deviation is the angle whose tangent is

$$\frac{0{\cdot}058}{42{\cdot}28} = \tan^{-1} 0{\cdot}001355 = 0{\cdot}078°.$$

This agrees sufficiently well for practical purposes with the result obtained by the method of moments.

In order to get exact figures for the relative amplitude of the electromotive force in phase A, B and C, we must assign the angle θ between the centre line of the phase-band and the slots 6, 7, 8, 9, 10 and 11. Then multiplying the cosines of these angles by the number of conductors at each point, we obtain the value 42·19 as against the value 42·28 for phases B and C. Thus we find that the amplitude of the electromotive force in phase A is less than the amplitude of electromotive force in B and C by an amount somewhat less than 1 part in 400.

The winding to which Fig. 206 refers has only one conductor per slot. If there were a number of conductors per slot it would be

possible to balance the phases still more closely by changing the number of conductors in some of the slots until the centre of gravity of the phase-band lay exactly on the dotted line. At the same time the amplitude of each phase can be adjusted to a nicety.

The presence of empty slots may be due either to the fact that there are more slots in the iron punchings than are wanted for the number of conductors chosen, or to the fact that they aid in balancing the phases. A great deal of ingenuity can be expended on the distribution of empty slots, particularly when there are more of them than are needed to balance the winding. The plan generally adopted when dealing with the problem by the method of moments is to regard an empty slot as creating a negative moment, which should be so placed as to assist in the balance. If it can be placed exactly on the dotted centre line its effect is zero. The further it is placed from the centre line the greater its effect. When there are too many of them, they may be made to balance one another on opposite sides of the centre-line.

Change in the number of phases.

It sometimes happens that a generator wound for a certain number of phases must be rewound to adapt it for a circuit in which the number of phases is different. At the end of the last century and in the early years of the present century, before the advantages of the three-phase generator were completely understood, a large number of two-phase generators were installed in the United Kingdom, America and other countries. Many of these machines have since been converted into three-phase machines, and there are still some left which may be converted in the future. When the number of slots per pole happens to be a multiple of three, it is possible to put in a standard three-phase winding. In the case of wave-wound machines such as often found in low-voltage generators—where the winding is of the type that might be closed on itself like a continuous-current machine, and in which the different phases are obtained by opening the winding at suitable points and bringing the ends to terminals, or in the case of mesh-wound armatures by leaving the winding a closed one and bringing out taps to the terminals —no special difficulty arises in changing from one number of phase to another, provided the number of slots per pole-pair is suitable (see page 198). But in the cases where the number of slots per pole (or per pair of poles) is not a multiple of three, and where the total number of slots is not suitable for a closed circuit winding, there is sometimes scope for a great deal of ingenuity in adapting the available slots so as to get a winding to give the right voltage, and at the same time preserve the balance of the phases.

The first step is to find approximately the number of conductors

required. In changing from a two-phase open type (phase-band 90°) armature to a three-phase star-connected (phase-band 60°) armature, the total number of conductors will in general be reduced to 0·81 times the number required for the two-phase machine. The number of conductors *per phase* will be only 0·54 times the conductors per phase in the two-phase machine. If, however, the machine has a closed winding and the two phases are obtained by tapping off at diametral points on two diameters at 90° to one another, and it is proposed to make a three-phase machine by tapping off at three points, 120° apart, then the three-phase voltage will be only 0·865 of the two-phase voltage, so that if the same voltage is required the number of conductors in the mesh-connected armature must be increased. The total number of conductors in the three-phase mesh-connected armature will be 1·15 times the conductors in the mesh-connected two-phase armature. These numbers are based on the assumption that the saturation of the magnetic circuit is to be the same for both machines. It will, however, be found in practice (especially when dealing with machines designed many years ago) that the state of saturation can be changed a good deal without seriously affecting the performance of the generator. Where a generator has been very liberally designed and has a very weak armature, the number of conductors may be increased somewhat above the figure prescribed by the above considerations. On the other hand, where the saturation of the magnetic circuit in the old machine is rather low, it may be an advantage to decrease the total number of armature conductors. The best plan is to take the magnetization and short-circuit curves of the machine and note the state of saturation at normal voltage and the amount of armature reaction. It can then at once be seen whether it is an advantage to depart from figures given above, and how far one may go in fixing the numbers to suit the arrangements that may be necessary for the purpose of balancing the phases.

Where the number of slots per pole-pair is not divisible by three, it is not possible to comply with the strict winding rules referred to on page 198. It is, however, nearly always possible to devise a winding which will give the right voltage at the right saturation of the field-magnet, and at the same time be sufficiently symmetrical for all practical purposes. The method of moments described on page 200 will be found of great service in complicated cases in getting the best possible distribution of the slots between the various phases and in the proper placing of empty slots. A diagram like that given in Fig. 206 reveals at once a number of equivalent alternatives, some of which may be much more convenient to carry out than others. By choosing the right alternative it is sometimes possible to use over again a large number of the old two-phase coils in the

new three-phase winding, thus saving the difference between the value of scrap coils and new coils, as well as a great deal of labour and time.

Bad wave-form.

It may happen that the wave-form of the E.M.F. of an A.C. generator contains higher harmonics of considerable amplitude. Undue stress may be thrown upon the insulation of the system, especially upon the insulation of certain lengths of cables whose inductance and capacity is of an amount to cause resonance with one of the higher harmonics. A fundamental frequency of 50 cycles is not in general high enough to bring about resonance in ordinary cables. But when a high harmonic (say the 23rd harmonic) is present and is of considerable amplitude, the inductance and capacity of certain feeders may be such as to bring about marked resonance effects. Fig. 207 shows the no-load wave-form * of the E.M.F., a

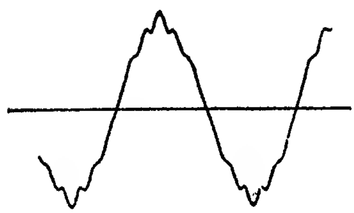


FIG. 207.

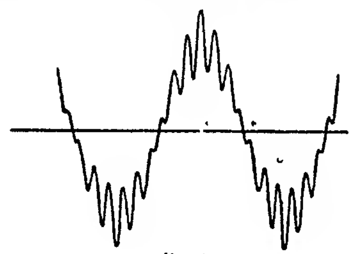


FIG. 208.

generator having six slots per pole. When this generator was switched on to certain cables whose capacity was such as to give partial resonance with the 13th harmonic, this harmonic was very much amplified, as shown in Fig. 208. The greatest danger occurs when for any reason the generator speed is varied over wide limits; because all the resonance points that lie between these limits belonging to different cables on the system must necessarily be passed through. For this reason it has been found very undesirable to start up and bring to speed a fully excited generator that is connected to a transmission line. It is quite likely that, at some speed between zero and full speed, resonance will occur between one of the harmonics and the natural period of oscillation of some branch of the distributing system. The breaking-down of cables has occurred through the slowing down of generators or synchronous motors connected to feeders. A case that may happen is the following: A synchronous motor is running light at the end of a long feeder, which is protected at the power-house end by a

* See W. Duddell, *Journ. Inst. Elec. Engrs.*, vol. 52, p. 2.

circuit-breaker. For some reason the circuit-breaker is opened, and the motor slows down, being fully excited and still cencedont to the feeder. As it slows down, all the harmonics on the E.M.F. wave-form gradually decrease their frequency, until one of them reaches the resonance frequency of the feeder and the voltage rises to a point high enough to break down the insulation.

The most common cause of pronounced higher harmonics in synchronous machines is the existence of open slots in the stator, especially when the shape of the field-form is such as to make higher harmonics in the field-form of the same order as those produced by the stator slots. Even when the slots are closed, or semi-closed, the fact that the conductors of the armature are spaced at definite intervals, instead of being uniformly distributed, may give rise to pronounced harmonics in the wave-form of the E.M.F.

If the field-form of a generator were of pure sine-wave shape, then it would not matter how the conductors on the armature were spaced; because the summation of any number of fundamental sine-waves, whatever their phase, can only give a pure sine-wave. If, however, the field-form contains any harmonic having a certain amplitude, the spacing of the winding may be such as to pick out that harmonic and reproduce it in the E.M.F. wave-form with undiminished amplitude in relation to the fundamental. It is important to be able to recognize the kinds of spacing of the armature conductors that produce these effects.

The matter can be shortly stated as follows: The danger arises when the number of slots per pole is a whole number, say Q. If the number of slots per pole is fractional, say $Q+\frac{1}{2p}$, where p is the number of pairs of poles, the danger is avoided.

Taking the case where the number of slots per pole is a whole number Q: if we have a pronounced h^{th} harmonic in the field-form, where $h=2Q\pm 1$, that harmonic will be picked out by the conductors and reproduced in the E.M.F. wave-form with undiminished intensity; because the winding factor (or breadth coefficient) for that harmonic is the same * as the winding factor (or breadth coefficient) for the fundamental sine-wave form of the field-form.

It generally happens that the amplitude of h^{th} harmonic in the field-form is small when h is great. Thus the amplitude of the 5th harmonic is commonly smaller than that of the 3rd, and the 7th is often smaller than the 5th. When the number of slots per pole, Q, is great, one does not expect to get trouble from marked ripples in the E.M.F. wave; because one hopes that the $(2Q+1)^{th}$ and the $(2Q-1)^{th}$ harmonics in the field-form are of small amplitude. This, however, may not be the ease. If there are teeth on the

* See Smith and Boulding, *Journ. Inst. Elec. Engineers*, vol. 53, p. 205 (1915).

surface of the field-magnet so spaced as to make these harmonics have considerable amplitude, that amplitude will go through to the E.M.F. wave-form, notwithstanding the high value of $(2Q+1)$.

It can be shown * that the winding factor for the $(2Q\pm3)^{th}$ harmonic is the same as for the 3rd harmonic. This is zero on a three-phase stator as usually wound, but may be as high as 0·7 in the phase voltage. For values of winding factors for various numbers of slots the reader is referred to the tables given by Dr. S. P. Smith and R. S. H. Boulding in their paper quoted above.

The ripples in the E.M.F. wave-form arising from the spacing of the armature conductors, as stated in the preceding paragraph, have been called by Smith and Boulding 'spacing ripples,' to distinguish them from 'tooth ripples' that arise from the rapid pulsations and oscillations of the field flux caused by the movement of the poles in front of the projecting armature teeth. When a pole is well shaped, so as to make the field-form sinusoidal, the effect of the projecting teeth is much reduced. It is however very difficult to shape a pole so as to completely eliminate the tooth ripple. The best plan is to skew the edges of the pole through exactly one slot pitch. Where the pole is provided with a bevel, the whole bevel must also be skewed exactly one slot pitch. A template should be prepared which gives the profile of the pole as seen in a section on a plane at right angles to the axis of rotation. This template should fit the pole on any section on a plane at right angles to the axis and to do this the template must be moved through a slot pitch in a circumferential direction as it is slid from one end of the pole to the other. Even when the greatest care is taken to shape the pole in this way it will be found that the field-form under a part of the pole at one end is not identical with the field-form under the part of the pole at the other end, because the state of saturation of the teeth is affected by flux which enters them in an axial direction.

Tooth ripples may be caused by slots in the pole face such as made for the purpose of inserting damper rods. If these slots have the same pitch as the armature slots the effect may be very pronounced. After the poles have been manufactured it may be a very difficult matter to skew the slots in the pole. The effect of such slots can be minimized by altering the spacing of alternate poles through one half of a slot pitch. Leaving all the North poles where they are, all the South poles may be moved circumferentially through one half of a slot pitch. The mechanical arrangements necessary to enable this change to be made may be somewhat difficult. Where the poles are solid it may be possible to arrange for new holes to be drilled in the yoke or spider the centres lying in a new plane at right angles on the axis at a sufficient distance from the plane of the old

* See Smith and Boulding's paper, *ibid.*

holes so as to avoid the difficulty of drilling new holes with centres too close to the old ones.

Regulation.

A.C. generators are often sold with a guarantee as to the percentage of variation of voltage between full load and no load, or from no load to full load.

"Regulation up." Where the guarantee is expressed by giving the percentage rise of voltage that will occur when full load at some stated power factor is thrown off, the guarantee is sometimes spoken of as relating to " regulation up."

"Regulation down." Where the guarantee is expressed by giving the percentage fall in the voltage that will occur when a machine, running light, is subjected to full load at a stated power factor suddenly thrown on, the guarantee is said to relate to " regulation down."

In both these cases the guarantee is usually given on the assumption that the speed and excitation remain constant.

Where a machine apparently fails to meet the guarantee, the first step that should be taken is to ascertain how far the variation of voltage on change of load is due to change in speed and change in excitation. The change in load invariably affects the speed of the prime mover; and where a machine is excited by means of a direct-connected exciter, a comparatively small change in speed may bring about a very considerable change in the exciter voltage. This is due to the factors discussed on page 245. In dealing with matters relating to the exciter, the reader is referred to the chapters on D.C. machines. Where the guarantee has been given on the basis of constant excitation, and it has been found that the exciting current changes with the load, it is permissible to restore the field current by means of the rheostat and read the change in voltage when running at the original field current. If the guarantee has been given on the basis of constant speed, it is legitimate to assume that the voltage changes in direct proportion to the speed, and to make a correction accordingly.

If, after these corrections have been made, the regulation does not fall within the guarantee, we are led to enquire into the shape of the magnetization curve and the short-circuit characteristic of the generator. The way in which these matters affect the regulation of machines can be shortly stated as follows:

Graphic construction to determine the full load field current. It is perhaps best in dealing with this matter to take an actual case so that concrete values can be given. We will take the case of a 500-K.W. 3-phase star-connected 2200-volt generator intended for a load whose power factor is 0·75; so that the K.V.A. rating of the

machine is 666, and the full-load current 175 amperes. Let the no-load magnetization curve of the machine be given by the curve in Fig. 202. We will suppose that the effective armature ampere-turns per pole * at full load are 3380. We will further suppose that the resistance per phase measured from the star-point to one of the terminals of the armature is 0·109 ohm, and that the resistance drop in one phase of the armature is $0{\cdot}109 \times 175 = 19{\cdot}1$ volts, or $19{\cdot}1 \times 1{\cdot}73 = 33$ volts at the terminals, so that the resistance drop is 1·5 per cent. of the normal voltage. We will further suppose that the magnetic leakage that occurs in the armature slots and around the end-windings at full load amounts to 7 per cent. of the working flux, so that we may take the reactive drop in the winding at full load due to the self-induction of the armature at 7 per cent. of 2200 or 154 volts. If we set off from the origin in Fig. 209 a horizontal line OI to represent to scale 175 amperes, we may mark off on this line a distance, OR, to represent to scale the 33 volts drop in the resistance, and another line at right angles to this, RL, to represent the reactive drop of 154 volts. We then arrive at OL, which gives to scale the impedance drop, equal to 157 volts. This is the voltage that must be generated in the armature when running on short circuit in order to drive a full-load current through the armature.

Let us suppose that there are 60 turns per pole in each field coil, so that the ampere-turns per pole required to generate 2200 volts at no-load are obtained by multiplying the field current $84 \times 60 = 5040$. It will be seen from Fig. 202 that it requires about 5 amperes excitation to generate 157 volts at no-load, so that the effective ampere-turns for this voltage are $5 \times 60 = 300$. When the machine is running on short circuit, however, the current is lagging by an angle of 78° behind the generated E.M.F., and the armature applies demagnetizing ampere-turns equal to 3300. We can now set out the 300 ampere-turns required to generate the voltage OL at right angles to OL,

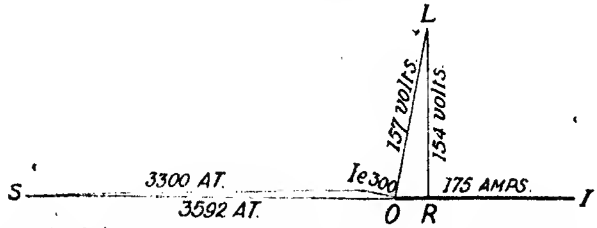


FIG. 209.—Scale: 1 cm. = 60 amperes; 1 cm. = 600 ampere-turns; 1 cm. = 60 volts.

as shown by the line OI_e in Fig. 209, and also the 3300 ampere-turns on the field-magnet required to overcome the armature turns, as

* See *Specification and Design of Dynamo-Electric Machinery*, p. 282.

shown by the line I_1S parallel to OI. The sum of these two, OS, equal to 3592, gives the total field ampere-turns per pole required to drive full-load armature current through the armature on short circuit. Dividing this by 60 turns, we get about 59 amperes for the field current on short circuit. The short-circuit characteristic to be expected in this machine is given by the line OS in Fig. 202. The short-circuit characteristic is ordinarily obtained by a test on the machine carried out as follows: The primaries of three series transformers are connected between the terminals and a conductor which short-circuits the three terminals (see Fig. 210). The secondaries of these transformers are brought to switches by which they can be successively connected to an A.C. ammeter. A D.C. ammeter is placed in the field circuit; the machine is run at full speed, and readings are taken of the armature amperes at various excitations. If the machine is perfectly symmetrical, all the three armature currents will be identical. In practice one finds that through dissymmetries there are slight differences between the currents. In this case it is usual to take the average current to represent the short-circuit value at any particular excitation. When dealing

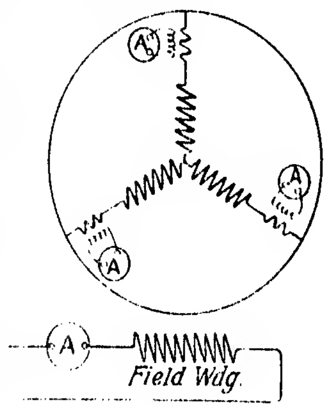


FIG. 210.

with armatures having a very low reactance and resistance, care must be taken to see that the total impedance of the series transformer taken in conjunction with the A.C. ammeter is negligibly small in comparison with the armature impedance. If this is not so, the armature current will be smaller on short circuit through the transformers than it would be if they were absent. It is quite easy, however, to correct the results by calculation if the impedance of the ammeter is known. Care must be taken that none of the cables employed to carry out the connections in Fig. 210 embraces an iron circuit. If, for instance, in making the connections one of the cables to a series transformer embraces the pedestal of the bearing, the self-induction of the cable will be increased, and this will lead to an unsymmetrical loading, especially in the case of low-voltage machines where the current is high. Where one ammeter is connected to the series transformers in succession, it is a good plan to short-circuit the secondaries of the other transformers through an impedance of an amount equal to the impedance of the ammeter. It is possible that the short-circuit characteristic of the 500-K.W. generator, parti-

culars of which are given above, might come out as shown by the curve OS', which is slightly concave on the upper side. This concavity of the short-circuit characteristic is caused by the saturation of the iron of the armature teeth and the consequent reduction of the reactance at higher currents. In practice one employs the short-circuit characteristic obtained from test rather than the calculated characteristic.

The simple short construction to find the full-load exciting current at any power factor is as follows: Lay off a horizontal line, as OI_e in Fig. 211, to represent to scale the field current required at normal voltage. This will be taken from the no-load characteristic; it will be 84 amperes in our case. At right angles to this set off a vertical line I_eE to represent the phase of the terminal voltage;

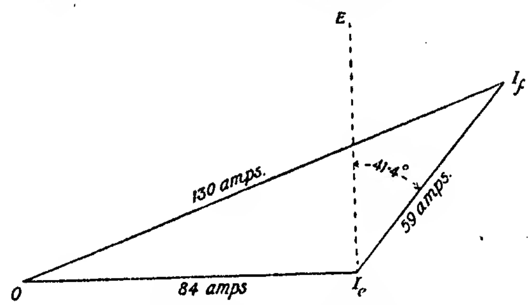


FIG. 211. Scale: 1 cm. = 15·5 amperes.

and to the right of this set off the angle of lag as shown in Fig. 211. For a power factor 0·75 this would be 41·4°. Then lay off the line I_eI_f equal to the field current required to drive full-load current on short circuit. This will be about 59 amperes in our case. Then OI_f is taken as the field current required at full load at the stated power factor.

This simple construction, though sufficient in many practical cases, leaves out of account the fact that the impedance of the armature, in calling for a generated voltage rather higher than the terminal voltage, causes the field system to be more saturated than it would be if the terminal voltage only were being generated; and thus the effective field amperes required to generate the voltage necessary to overcome the impedance of the armature will be greater than they would be if the field had not been so saturated. A more accurate construction,* therefore, is as follows: Lay off the line OE_t to represent the terminal voltage 2200 to scale, as in Fig. 212. To the right of this set off the armature amperes OI_a lagging by the required angle. Draw the line E_tE_x at right angles to OI_a to repre-

* When the generator has salient poles, it is necessary to make a further correction to allow for the greater reluctance for the cross flux. This can be done in the manner illustrated in Figs. 118 to 120, but in the case of a generator OI must be drawn downwards from O.

sent to scale the reactance drop in the armature, and the line $E_t E_g$ to represent the resistance drop; then the line OE_g represents the voltage required to be generated in the armature. In our case OE_g comes out at 2290 volts. Referring to the magnetization curve, Fig. 202, we see that to generate 2290 volts at no-load would take a field current of 95 amperes. It is known, however, that when running on full load the leakage from pole to pole is considerably greater than at no-load; so that the ampere-turns absorbed by the iron of the poles and yoke are greater at full load than at no-load,

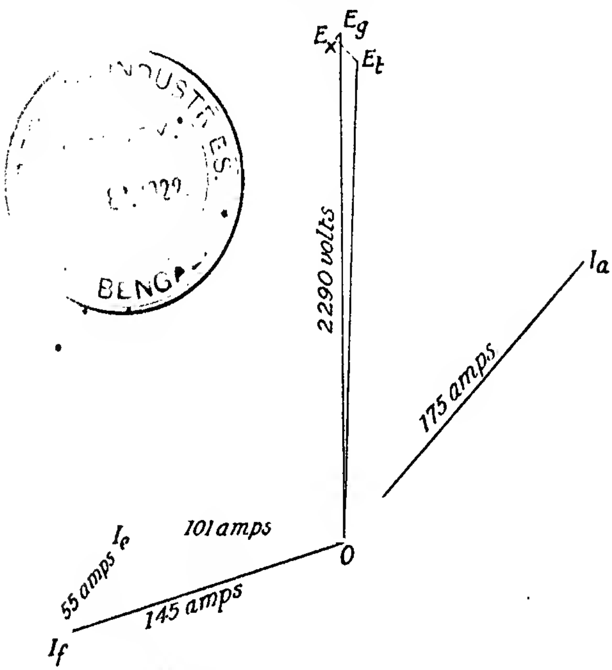


FIG. 212.—Scale: 1 cm. = 30 amperes; 1 cm. = 300 volts.

even for the same voltage generated. If we had all the design data, we should be able to make an allowance for the extra ampere-turns so required, and we should find that the magnetization curve for a given load at a given power factor would lie to the right of the no-load magnetization curve for full load 0·75 power factor. The new magnetization curve might be that indicated by NN' in Fig. 202. Where no exact design data are available, an estimated allowance may be made for this increase of field current due to the increased saturation of the poles brought about by leakage on load. Taking the new magnetization curve NN', we see that the field current

required to generate 2290 volts is 101 amperes. We set off this current at right angles to the line OE_o, as shown at OI_e in Fig. 212, and draw a line I_eI_f parallel to I_aO. The length of I_eI_f should be 55 amperes, which is obtained by dividing 3300 by 60; thus we get OI_f, which represents to scale the required field current at full load at 0·75 power factor. This comes out at 145 amperes, as against 130 amperes obtained by the short method, which did not take into account the extra saturation of the machine.

We see now that if the machine is run at full load at 0·75 power factor at 2200 volts and the load is suddenly switched off, the voltage will rise to 2610. If we wish to know how much the voltage will fall when the machine running unloaded at 2200 volts has full-load current at 0·75 power factor suddenly switched on, we have to make the construction shown in Fig. 213. Set off the line OI_a, making an

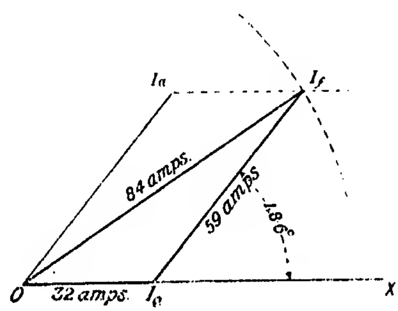


FIG. 213.

angle 48·6° with the horizontal line OX. The line OI_a represents the short-circuit field current, 59 amperes. Through I_a draw a line parallel to OX. With O as centre draw a circle having a radius representing 84 amperes. This intersects the horizontal line I_aI_f at the point I_f. Join OI_f. Complete the rectangle $OI_aI_fI_e$; then OI_e represents the resultant excitation after the armature demagnetizing effect (59 amperes) has been subtracted from the applied excitation (84 amperes). From Fig. 213 we see that OI_e is 32 amperes, which, according to Fig. 202, would give us 1000 volts on the generator. We see from constructions given in Figs. 212 and 213 that whereas the voltage rise with load thrown off is only 18·5 per cent., the voltage fall with load thrown on is 54·5 per cent.

Remedies for poor regulation. When an A.C. generator fails to meet the regulation guarantee, the no-load magnetization curve and the short-circuit characteristic should be taken. If it should be found that the field ampere-turns required to drive full-load current through the armature are greater than was expected, it is not possible to rectify the defect without making fundamental changes in the

design. It is not in general permissible to cut out armature coils so as to substantially reduce the armature reaction, because we should create local disturbances in the flux distribution, which would be very undesirable, and might cause undue heating of the field-poles. Where the alteration required is very slight, an odd coil can be cut out from each phase. The coils cut out should be distributed so as to make the least possible disturbance at any one part of the armature. As regulation is not an important matter, it is preferable not to disturb the symmetry of the machine. If it were permissible to alter the design of the machine so as to reduce the number of conductors in each slot, this would be by far the most effective method of improving the regulation; because by doing so we should not only reduce the armature ampere-turns, but (by calling for a greater flux to generate the voltage) increase the field ampere-turns and also the amount of saturation.

It may be found that the field-amperes required to give full voltage at no-load are smaller than was expected. This would have the effect of spoiling the regulation. Before we can tell whether it can be remedied by increasing the air-gap, we must know whether the field-magnet is well within the temperature guarantee at full load. If it is found after a full-load test that the temperature rise of the field coils is well below the guarantee and that the field current could be substantially increased without interfering with the efficiency guarantee, steps may be taken to increase the no-load field current by lengthening the air-gap. Where only a small increase in the field current is required, it may be sufficient to put the whole field-magnet in a lathe and cut away a little metal from the pole faces. The objection to this procedure is that the amount of bevelling of the poles is altered; and to re-bevel the poles is a rather expensive operation. In many cases, however, a small amount of change in the bevel does not affect the practical operation of the machine. When calculating how much metal should be cut away in order to increase the field current by a certain percentage, regard must be had to the amount of saturation in the magnetic circuit and also to the amount of bevelling of the poles and the ratio of pole-arc to pole-pitch. As these are matters of design, they hardly fall within the province of this book. For ordinary ratios of pole-arc to pole-pitch and normal amounts of saturation, it will be found that it is necessary to increase the length of air-gap by $1\frac{1}{2}$ per cent. in order to increase the field current by 1 per cent. When the poles are bolted on, there are sometimes liners underneath them, and the air-gap can be increased by taking out the liners. If no liners are provided, the poles may be taken off and the spider turned down. This plan has the advantage of not interfering with the bevels of the poles. The increase in the air-gap has very little effect upon the short-circuit

characteristic. The regulation is improved; because the ratio of OI_e to I_eI_f in Fig. 211 is increased, so that the ratio of OI_f to OI_e is diminished.

Interchange of load.

We propose to consider under this heading the factors that determine the amount of wattless and wattful load taken by each generator when a number of synchronous generators are connected in parallel to the same busbars.

True load or "wattful" load. The wattful load carried by a synchronous generator is dependent upon the power supplied by the prime mover, and is independent of the excitation of the generator; always supposing that the excitation is sufficient to hold the machine in synchronism. When an alternator is being synchronized for the purpose of being connected to busbars, the supply of steam to the prime mover is just sufficient to overcome the friction and iron losses and to run the machine at the synchronous speed. After the main switches are closed and the machine runs in synchronism with the busbars, no load will be taken by it until the steam supply is increased. The increased torque supplied by the extra steam pushes forward the field-magnet so that its centre line is in advance of the vector which represents the E.M.F. on the busbars (see page 171). The vector difference * of the generated E.M.F. and the busbar E.M.F. is the E.M.F. available for driving current through the impedance of the armature windings.

The greater the supply of steam, the greater the turning moment and the greater the displacement of the field-magnet position with reference to the vector representing the busbar voltage, and in consequence the greater the wattful current generated by the machine. If the steam supply is completely cut off, the centre line of the poles will fall behind the vector representing the busbar voltage. The machine will now run as a motor and drive the engine. The change in the excitation of the generator cannot make any permanent change in the amount of load carried by the machine, for this can never be either more or less than the power supplied by the prime mover. It sometimes happens that engineers who are familiar with the running of D.C. generators, and who have but newly come to an A.C. power-station, will increase the excitation of the generator after connecting it to the busbars, in the hope of putting it on load. It is true that the ammeter swings over the scale as the field current is increased, because the amount of wattless current yielded by the machine is increased; but the wattmeters do not show any increase of load until a further supply of steam is given to the generators.

* *Specification and Design of Dynamo-Electric Machinery*, p. 338.

Wattless load. The wattless load yielded by a synchronous generator when connected to busbars in parallel with other generators depends mainly upon the excitation of the field-magnet. An increase in the excitation of the field-magnet beyond the point necessary to give unity power factor at the load for the time being carried by the machine will cause the generator to supply a lagging current. A diminution of the excitation below the value required for unity power factor at the load for the time being carried by the generator will cause the generator to take a current from the line which is leading with respect to the generator E.M.F. and lagging with respect to the busbar E.M.F. The graphic constructions which enable one to determine the amount of wattless current that will be taken by a generator under various conditions of load and excitation are shown in Figs. 115 to 121, and Fig. 212.

Sharing of the load. A complaint that is sometimes made against synchronous generators running in parallel on the same busbars is that they do not evenly share the load when the total load on the station changes. In considering the performance of the machine in this respect, one must carefully distinguish between the behaviour as to wattful load and the behaviour as to wattless load.

In order to make the sharing of the **wattful load** satisfactory, we must look to the **governors** of the prime movers. Steam governors and water governors are ordinarily constructed so that a reduction in speed of the prime mover causes an increase in the supply of steam or water. It is usually possible to adjust the sensitiveness of the governor so that a fall in speed of 1 per cent. will result in a greater or smaller increase in turning moment. For instance, the governor of the steam engine may be set so that a drop in speed of $2\frac{1}{2}$ per cent. will turn on a full-load steam supply; whereas another adjustment may require a drop of $3\frac{1}{2}$ per cent. in order to turn on the same steam supply. If a number of generators of the same rating are to be run in parallel, it is desirable that all the governors shall be set so as to supply the same steam for the same drop in speed. If they are not so set, the generator having the finer governor-setting (that is to say, with a governor set for a smaller drop in speed for full load) will take a greater wattful load. Where machines are of different rating, the sensitiveness of the governors should be adjusted so that for the same drop in speed the steam supplies to the respective generators are in proportion to the rated loads.

Trouble sometimes arises through the peculiarities of the governor characteristics. Steam supply on a governor is rarely in strict proportion to the percentage change of speed. The governor on generator A may be more sensitive on light loads than the governor on generator B; while the governor on generator B may be more sensitive on heavy loads than the governor on generator A. Thus,

on the light loads generator A would tend to take more than its share of the load; and not until we reach the heavier outputs will the machines share the load equally. Small differences in sensitivity are not of great practical importance, as it is not really necessary *that all machines shall share the load exactly in proportion to their rating without attention; especially as the amount of load taken by any machine is directly under control of the switchboard attendant, who has a means of changing the setting of the governor for this purpose.*

Sharing of wattless loads. Where generators of different ratings or of different makes are running in parallel on the same busbars, it is very rarely that they will share the wattless load evenly without adjustment, as the load in the station changes. This is because the short-circuit characteristics are usually different in machines of different design. As stated above, the amount of wattless current yielded by a given generator depends upon the excess of excitation over that required to yield unity power factor at the load for the time being on the machine. The amount of excitation required at any given power factor can be ascertained from the construction given in Fig. 212, if the characteristics of the machine are known. It will be seen from this figure that where the ratio of armature ampere-turns to field ampere-turns is great, the percentage change in excitation when the machine is put upon full load at any given power factor is greater than in the case where the ratio of armature ampere-turns to field ampere-turns is smaller. If, therefore, we take two machines, A and B, of the same rating, both having the same number of ampere-turns on the field-magnet at no-load, but A having twice as many armature turns as B, the machines when running in parallel driven by equal prime movers with perfectly set governors will not share the load evenly unless the excitation of A is increased as load comes on in a greater ratio than the excitation of B. For this reason each machine should be provided with its own power-factor meter; and the station attendant, while seeing that each generator takes its share of the wattful load by having a proper steam supply, should also see that each takes its share of the wattless load by having its excitation suitably adjusted.

If the principles enunciated above are clearly understood, there is not much difficulty in interpreting the symptoms that appear in defective distribution of load between synchronous machines. Two examples will serve to illustrate the kind of defects met with in this connection, and the way of curing them. Suppose that two 5000-K.W. 3-phase turbo-alternators, A and B, generating 6600 volts are running in parallel on the same busbars and are adjusted to divide the load equally when running at half their rated capacity. The load on the station suddenly increases to 14,000 K.W. It is then found that one

machine, A, is taking 9000 K.W., and the machine B only 5000 K.W., as shown on the indicating wattmeters; and on a further momentary increase of load the overload breakers on machine A, which have been set at double full load, come out, with the result that all the load is thrown on to B and the breakers on B have also come out, shutting down the supply. As we are dealing here with wattful load as indicated on the wattmeters, it is clear that the governors are at fault. In all these cases it must be remembered that as synchronous machines must necessarily all run at the same speed we must enquire into the characteristics of the governors and the steam supply to the two machines when running at a particular ascertained speed. The makers of the turbines will be able to supply the characteristic curves of the governors; these are generally given in the form of a curve plotted with load as abscissa and speed as ordinates. The governor is generally capable of adjustment, so that the slope of the curve can be adjusted within certain limits. It will be found in this case that the slope of the curve for the B governor is very much greater than the slope for the A governor; so that the change of speed of the whole plant, which occurs between half-load on the station and 40 per cent. overload, corresponds on governor A to a change of load from 2500 K.W. to 9000 K.W., whereas on B the same change of speed corresponds to a change of load from 2500 K.W. to 5000 K.W. The obvious remedy is to ask the makers to adjust the sensitiveness of the governors so as to make the slope of the two curves approximately the same.

For the second example, we may imagine the same two machines with the governors perfectly adjusted so as to take half-load at 0·8 power factor. Each machine delivers 275 amperes. Suddenly there is an increase of load to 40 per cent. overload on the busbars, the power factor being now 0·85. The total current from the busbars is now 1440. Suppose that, instead of being equally divided between the machines, 866 amperes is taken by machine A and 634 by machine B. Note should be taken of the wattmeter readings. Let us suppose that each wattmeter reads about 7000 K.W. This shows that the governors are properly adjusted and that each machine is getting the same supply of steam. The K.V.A. of machine A is 9900, and the K.V.A. of machine B is 7250. It is clear that A is taking too great a share of the wattless load and is in danger of bringing out its breakers; whereas B is running on a power factor very near to unity. By weakening the field of A and strengthening the field of B we can adjust the wattless load between them; but if the two machines have not the same regulating characteristics the sharing of the wattless load will vary with every change of the load on the busbars. In this case it is clear that generator A has much better regulating characteristics than generator B; and thus, on a sudden

increase of load on the busbars from 6250 K.V.A. to 15,500 K.V.A., generator *A* takes a wattless K.V.A. of 685 to weaken its field-magnet to the same extent as the field-magnet of *B* is weakened by a load of almost unity power factor.

It not uncommonly happens that generators having characteristics as different as this have to run in parallel; and no great difficulty arises as long as the changes of load are not very great and very sudden. When each generator has its own exciter under the control of a Tirrill regulator, it is possible to adjust the characteristics of the exciters so as to minimize the effect of the difference in the characteristics of the generators.

Failure to run well in synchronism.

In these days of turbo-generators with their few poles and their prime movers of even turning moment, one does not hear as much of bad synchronous running as in the days of slow-speed engines with quick cut-offs and long-drawn-out indicator diagrams. Nevertheless trouble sometimes arises when a new turbo-generator is installed to run in parallel with slow-speed engines installed some time ago. The flywheel effects of the old engines may have been adjusted so that they run well enough between themselves, but the turning moment is so irregular that the new turbo-generator will cause bad phase-swinging unless the constants of the circuit and the flywheel effects are carefully looked to.

The high thermal efficiency of the internal combustion engine and the possibility of using coke-oven gas for power purposes, have led to the installation of very big gas engines. As these are for the most part machines of comparatively slow speed, the old trouble which used to occur when slow-speed engines drove alternators in parallel will occur again unless suitable precautions are taken. The problem of the parallel running of slow-speed alternators is, however, much better understood in these days than it was twenty years ago. It can be confidently asserted that where proper precautions are taken no trouble need arise on this score.

The turning moment of a reciprocating engine. The trouble most commonly met with in the parallel running of alternators is that due to resonance with the periodic impulses set up by the mechanism of the prime mover. A reciprocating steam engine or gas engine has an uneven turning moment. Even where there are four or six impulses per revolution, the combined turning moment is not uniform. Fig. 215 shows the turning moment of a 1500 B.H.P. gas engine having six pairs of tandem cylinders and six cranks, built by the National Gas Engine Company. It is direct-connected to a 1000-K.W. 40-cycle 3-phase generator. Each cylinder works on an Otto cycle, so that the crankshaft receives six impulses per revolution.

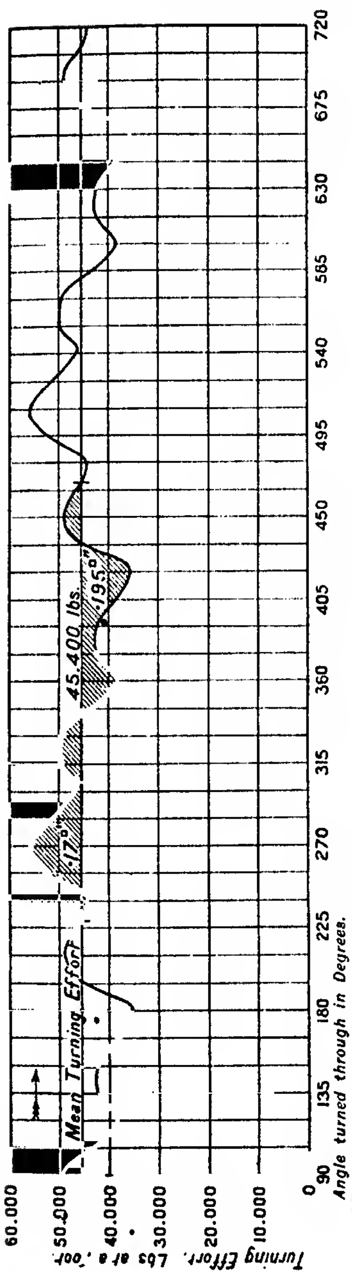


Fig. 215.—Turning-moment diagram of a 12-cylinder gas engine having six cranks, each cylinder working on an Otto cycle (National Gas Engine Co. Ltd.).

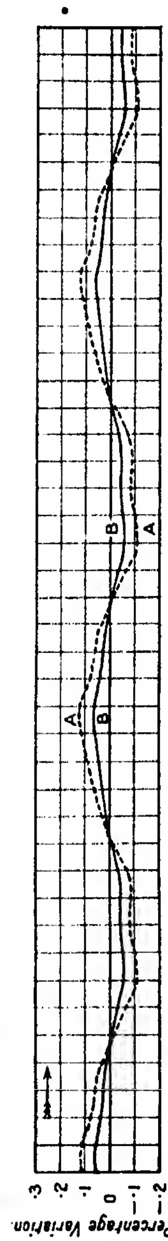


Fig. 216.—Speed variation curves derived from Fig. 215, curve A with a 131-ton ft.² flywheel and curve B with a 262-ton ft.² flywheel.

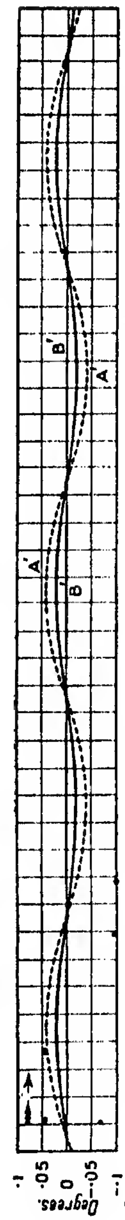


Fig. 217.—Angular deviation from uniform motion. Curves A' and B' are derived from curves A and B respectively in Fig. 217.

Fig. 218 shows the turning moment derived from one pair of cylinders *when yielding a little over full load, after taking into account the* accelerating forces on the moving parts and the effect of the cushion cylinder. The abscissae give angles turned through in degrees, and extend to two complete revolutions, or 720°. From 3° to 183° we have a positive torque derived from the explosion in cylinder *A*. From 183° to 290° we have a negative torque caused by the acceleration of the pistons and the compression in cylinder *B*; from 290° to 350° we have a positive torque derived from the cushion cylinder and the deceleration of the pistons. Then comes a short period of negative torque, where the compression torque is greater than the positive torques. From 363° to 543° the explosion in cylinder *B* provides a positive torque, followed again by a negative torque, and so on. In Fig. 215 the effect of all twelve cylinders is combined, giving an average turning moment of 45,400 lbs. at a foot radius. As the speed of the engines is 200 revs. per min., this corresponds to

$$\frac{45{,}400 \times 2\pi \times 200}{33{,}000} = 1728 \text{ Indicated Horse-Power.}$$

The turning moment varies from 10,000 lb.-ft. below the average to about the same above the average; but, owing to the number of cylinders, the periods of excess torque and of deficient torque are of short duration. The diagram may be regarded as a very satisfactory one for an internal-combustion engine. The change in the speed brought about by these periods of excess and deficiency will of course depend upon the moment of inertia of the rotating parts.

Expression of flywheel effect. Different systems of units are employed by different makers for expressing the amount of flywheel effect. It is convenient to consider these here, and to give the constants by which we get from one method of expression to another.

First, the moment of inertia of the flywheel may be given either in British or in metric units. The moment of inertia about the main axis is the sum of all such terms as mr^2, where m is the mass of a small piece of the flywheel and r is the radial distance of the mass from the principal axis. In England it is commonly expressed in tons at a foot radius². A rim weighing one ton at a radius of 4 feet would have a moment of inertia of 16 tons at a foot radius². On the Continent it is usual to express the moment of inertia of a flywheel in metric tonnes at a certain diameter² expressed in metres. When given in this way, we speak of the moment of inertia as being so many GD^2. A wheel weighing 1 British ton at a radius of 4 feet would be 1·016 metric tonnes at 2·44 metres diameter, and would be equivalent to 6·05 tonnes at 1 metre diameter, or 1510 kilograms at a metre radius². Therefore, to convert from GD^2 units to British tons at a foot we must multiply by 2·65. To convert from British tons at a foot to kilograms at a metre, multiply by 94·4.

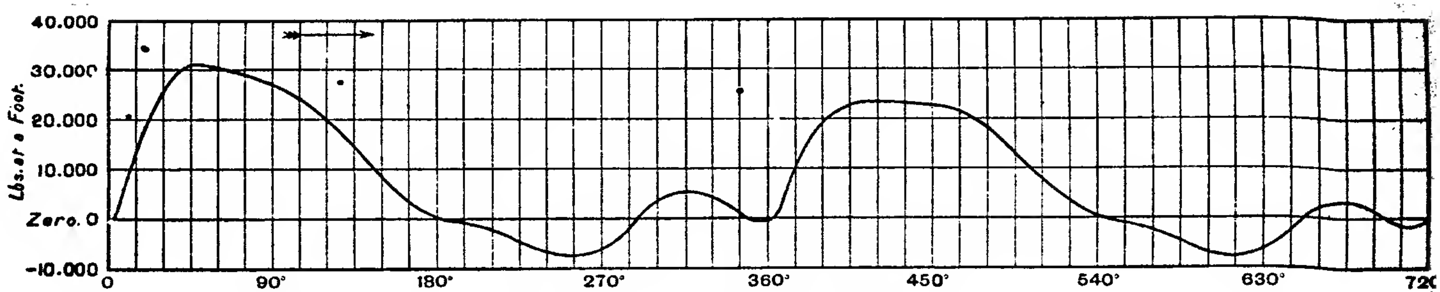


Fig. 218.—Turning moment due to one pair of cylinders.

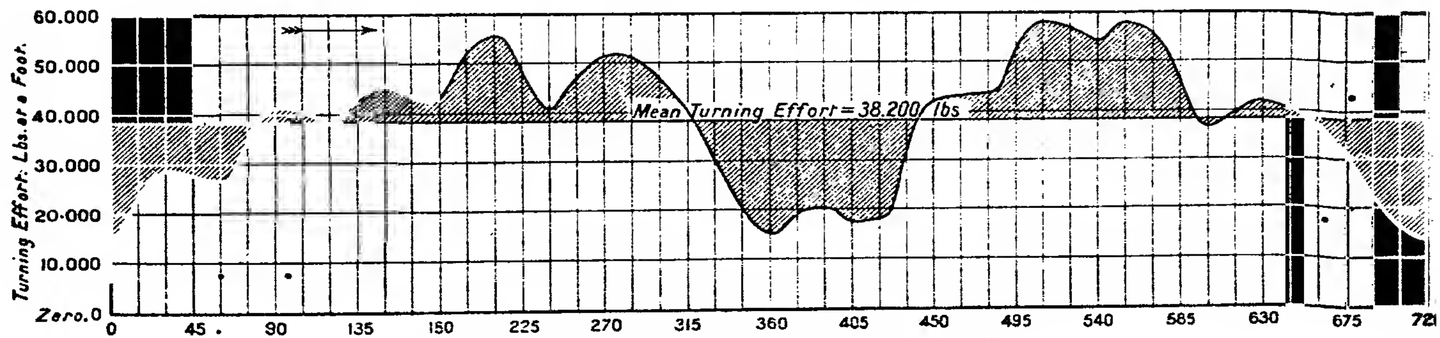


Fig. 219.—Turning-moment curve with one pair of tandem cylinders out of action.

Secondly, the flywheel effect may be expressed by saying how much energy is stored in it when it is running at a certain speed, say the normal speed for which it is designed. The energy may be expressed either in foot-pounds or in foot-tons; or, if metric measure is preferred, it may be expressed in kilogram-metres. If the moment of inertia M_r' is expressed in tons at a foot², the energy when revolving at R_{ps} revolutions per second is given by the following formulae:

$$\text{Foot-tons of energy} = \tfrac{1}{2}\frac{M_r' \times 4\pi^2 \times R_{ps}^2}{32 \cdot 2}.$$

$$\text{Foot-lbs. of energy} = \tfrac{1}{2}\frac{M_r' \times 4\pi^2 \times R_{ps}^2}{32 \cdot 2} \times 2240.$$

If the moment of inertia is given in GD^2:

$$\text{Foot-tons of energy} = \tfrac{1}{2}\frac{GD^2 \times 4\pi^2 \times R_{ps}^2}{32 \cdot 2} \times 2 \cdot 65.$$

$$\text{Kilogram-metres} = \tfrac{1}{2}\frac{GD^2 \times 4\pi^2 \times R_{ps}^2}{4 \times 9 \cdot 81} \times 1000.$$

Speed variation curve.

In Figs. 216 and 217 the effects of two different flywheels are considered.

Taking first a flywheel that gives to the whole rotating part a moment of inertia equivalent to 131 tons at a foot radius, the speed variation curve is given by curve A (Fig. 216). This curve is obtained by integrating the curve in Fig. 215. In order to get the right scale, let ω_m be the mean speed in radians per second and ω_d a small increase in speed. The speed at any instant is $\omega_m + \omega_d$. The stored energy in foot-tons

$$= \tfrac{1}{2}\frac{M_r' \times (\omega_m + \omega_d)^2}{32 \cdot 2}.$$

The gain in stored energy is

$$\tfrac{1}{2}\frac{M_r' \times (2\omega_m\omega_d + \omega_d^2)}{32 \cdot 2},$$

and where ω_d is small as compared with ω_m, we may take the gain in energy as

$$\tfrac{1}{2}\frac{M_r' 2\omega_m\omega_d}{32 \cdot 2}.$$

The energy given to the flywheel by the excess torque acting through a given angle is proportional to the area of a section of the turning-moment curve lying above the mean line; and the loss of energy of the flywheel is given by the area of the turning-moment curve lying below the mean line. The constant by which the area must be multiplied to get the gain or loss in energy in foot-tons is obtained as follows: In Fig. 215 one inch of ordinate corresponds to a torque

of 30,000 lbs. at a foot radius, and one inch of abscissa corresponds to an angle turned through of 1·57 radians. Therefore one square inch of area represents 47,100 foot-lbs. of energy, or 21 foot-tons.

It is convenient to begin to plot the speed-variation curve (Fig. 217) at a point where the speed is a maximum. This will be at the position 340°, immediately at the close of a long positive-torque period.

Area in sq. ins. of section of curve × 21 foot-tons

$$= \frac{131 \times 20\cdot95 \times \omega_d}{32\cdot2}$$

Here we have inserted for ω_m its value 20·95 radians per second. Thus, area of section of curve × 0·245 = ω_d.

Or if we wish to express the change in speed as a percentage of the mean speed:

Area of section in sq. ins. × 1·17 = percentage change in speed.

Thus, after the period of deficient torque represented by the area 0·195 sq. in. enclosed by the turning-effort curve in Fig. 215, the change in speed is

$$0\cdot195 \times 1\cdot17 = 0\cdot228 \text{ per cent.}$$

By running a planimeter around the sections of area bounded by successive ordinates of the torque curve, we can get successive values of ω_d or the percentage change in speed from point to point. We then draw a mean line to represent the mean speed.

The change in speed in Fig. 216 is plotted to the scale, one inch of ordinate = 0·6 per cent. change in speed. For one inch of ordinate, ω_d = 0·126 radian per sec. gain in speed.

Curve of deviation from uniform motion.

The time-scale is 1 inch = 0·075 second. Therefore 1 sq. in. of area under curve A is equivalent to 0·00945 radian or 0·54° of deviation from the position of uniform motion. By integrating the curve A in Fig. 216, using this constant, we obtain the curve A' in Fig. 217, which shows the deviation of the flywheel from an imaginary flywheel running at a constant speed. The scale to which it is plotted is 1 inch = 0·3° of deviation. It will be seen from curve A' that with a flywheel having a moment of inertia of 131 tons at a foot² the maximum deviation of the rotating part is 0·04 mechanical degree either way. As the machine has 24 poles (= 12 pairs of poles), this is equivalent to 0·04 × 12 = 0·48 electrical degree.

If we now take a flywheel of double the moment of inertia, that is to say, 262 tons at a foot², and having 4,000,000 foot-lbs. of stored energy at 200 revs. per min., we get the speed variation curve B in Fig. 216, and the deviation curve B' in Fig. 217, which shows a

maximum deviation of 0·02 mechanical degree, or 0·24 electrical degree. This is an exceedingly small deviation for an internal-combustion engine working on an Otto cycle. Many of these engines are driving alternators in parallel in an eminently satisfactory manner.

The curve in Fig. 215 gives the turning moment of a 12-cylinder gas engine when all cylinders are working. If for any reason one pair of tandem cylinders is missing fire or is out of action, the turning moment is much more uneven. Fig. 219 gives the turning moment curve under these conditions. The mean torque is now only 38,200 lbs. at a foot. The maximum deficiency in torque is 26,000 lbs. at a foot. The speed variation curve with one pair of cylinders out of action is given in Fig. 220, the method of plotting it being the same as described on page 222. Curve A relates to the case where the flywheel has a moment of inertia of 131 tons at a foot², and curve B to the case where the flywheel effect is doubled.

The deviation of the flywheels from the position of a uniformly rotating flywheel is shown by the curves A' and B' in Fig. 221. It will be seen that the heavier flywheel, even under these stringent conditions, has a maximum deviation of only 0·14 mechanical degree, or 1·68 electrical degrees on a 24-pole machine. It is generally supposed that a maximum deviation of not more than 2·5 electrical degrees may be taken as evidence of sufficient steadiness in the engine to permit of good parallel running.

Resonance. A very much more important matter than the amount of deviation calculated in the way described above is the presence or the absence of resonance between the disturbance and the natural phase-swing of the machine. If there is no resonance, the deviation as calculated above may be greater than 2·5 electrical degrees without leading to trouble in parallel running. On the other hand, if there is resonance, the actual deviation may be so magnified by the resonance as to make parallel running impossible, even when the periodic disturbance is so small as to be hardly visible on a curve plotted in the manner described in connection with Fig. 217.

Where the resonance is not so pronounced as to throw the machines out of step, it may magnify comparatively small disturbances, so that their effect is very visible on the speed curve, while greater disturbances that are not in resonance appear on the speed curve in their true proportions. This is very well illustrated by the tachograph record (Fig. 222) taken on a gas engine driving an alternator which was running in parallel with another alternator driven by a similar gas engine. Both engines had twelve cylinders and six cranks. As all the cylinders were apparently working well, the turning-moment diagram would not be very different from that given in Fig. 215. Perhaps one cylinder might be getting rather better explosions than the others; so that if we were to give to one

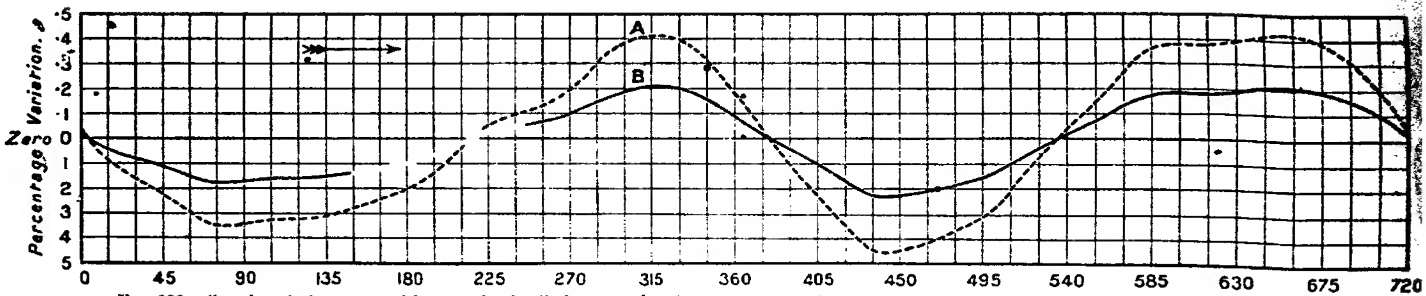


FIG. 220.—Speed-variation curve with one pair of cylinders out of action ; curve A with 131-ton ft.^{2} flywheel and curve B with 262-ton ft.^{2} flywheel.

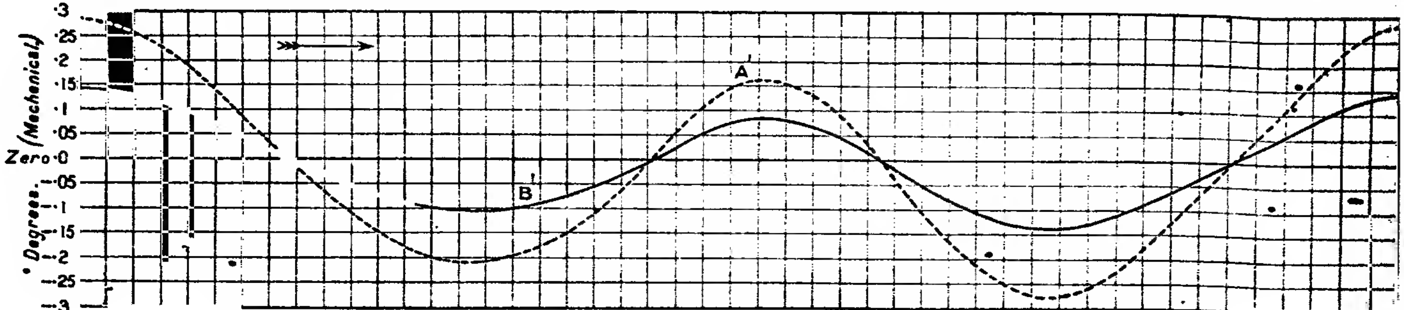


FIG. 221.—Curve of deviation from uniform motion. Curves A' and B' are derived from curves A and B respectively in Fig. 220.

of the three excess torque areas an area 20 per cent. greater than the others, the irregularity in the torque would be sufficiently well represented. The flywheel capacity of each set was such as to give a frequency of phase-swing not very different from the frequency of the camshaft, which in this case was 100 per minute.

It will be seen from the tachograph record in Fig. 222 that the main speed variation has a frequency of 100 per minute. The *maximum speed variation is about 0·5 per cent. from the mean, and* this is caused by an irregularity in the torque, which is probably not one-fifth of the irregularity that occurs every third of a revolution, due to the explosions in the cylinders. There are two reasons why the comparatively small disturbance produces such a great effect: (1) because a disturbance of low frequency has more effect in changing the flywheel speed than a disturbance of high frequency (see page 231); and (2) because there is partial resonance between the small disturbance and the phase-swing of the alternator, both having a frequency of about 100 per minute (see page 230).

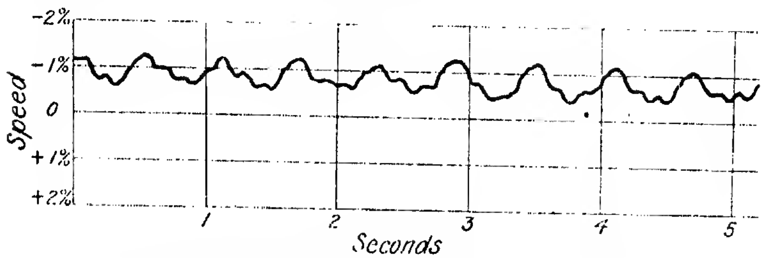


FIG. 222.—Tachograph record of generator when running in parallel with a similar generator, the natural period of phase-swing being about 0·6 second.

When the generator was run by itself on a dead load, there being no possibility of resonance, the speed curve (see Fig. 223) showed cyclical variations of not more than 0·1 per cent., having a frequency of three per revolution. The variations having a frequency of 100 per minute were barely perceptible upon the diagram.

When several generators were running in parallel on the busbars, it was found that the swinging of the wattmeters was very erratic. The biggest swings had a frequency of 100 per minute; but superimposed upon these were small excursions whose frequency was higher. For certain excitations of the field magnet, the swinging of the wattmeter needles became very violent, and occasionally a circuit breaker would come out on reverse current, and it would be necessary to again synchronize the generator that had been cut out.

This unsatisfactory state of affairs was obviously due to the fact that the flywheel effect was too near to the critical flywheel effect that would give perfect resonance with a disturbance having a

frequency of 100 per minute. The phase-swinging was also aggravated by the fact that the poles of the generator were not fitted with amortisseurs. Any little disturbance in the torque, due to a change in the pressure of the gas going to the engines, caused a swing that was a long time in dying out; so that its effect was added to another disturbance occurring a few seconds later, and these were perhaps added to a third, the combined effect being sufficient to send the wattmeter needles hard over.

It was therefore decided to put new flywheels on the sets and to add dampers to the poles of the field magnet. The method of arriving at a suitable flywheel and of estimating the improvement that would be expected from the new arrangement is described later (pages 235 to 238). The flywheel chosen gave a total moment of inertia equivalent to 393 tons at a foot radius².

After the changes had been made, it was found that the machines ran well in parallel with one another; and even when a cylinder occasionally missed fire the generators were not thrown out of step.

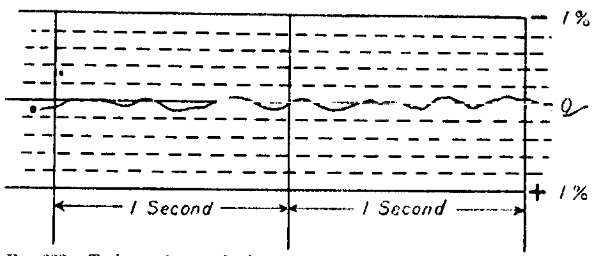


FIG. 223.—Tachograph record of generator when run on a tank load. There being no resonance the speed variation is only about 0·1 per cent. from the mean.

The effect of the dampers in reducing the amplitude of successive swings after a kick due to a big momentary disturbance was very noticeable on the wattmeter needles. These settled down immediately after a kick arising from irregular gas pressure.

In order to make an intelligent investigation into the causes of troubles arising from phase-swinging, it is necessary to understand the elements of the theory of phase-swinging.

Theory of phase-swinging.

We have seen on page 172 that a synchronous generator or motor is held in step by a synchronizing current, which is almost proportional to the angle σ by which the revolving part is displaced from the synchronous position, so that it behaves like the balance-wheel of a watch whose spring-control is almost proportional to the angular displacement: that is to say, when displaced and released it swings

about the synchronous position at a definite frequency. The greater the synchronizing current for a given displacement, the higher the frequency of the phase-swing. The greater the moment of inertia of the rotating part, the lower will be the frequency of the phase-swing. In a machine having p pairs of poles,

$$\sigma = p\alpha,$$

where α is the mechanical displacement of the rotating part. Let us denote by c the constant by which we must multiply α in order to get the synchronizing torque. Then, from page 172,

$$Q_s = \frac{EI_u p\alpha}{9{\cdot}81 \times R_{ps} \times 2\pi} = c\alpha \text{ kilograms at a metre radius.}$$

Natural period of phase-swing. Let us take the mass m of each part of the rotating part in kilograms, and its distance r from the centre in metres, and denote the moment of inertia by Σmr^2. Then the turning moment (in kilograms weight at a metre) required to give a unit angular acceleration is

$$\frac{\Sigma mr^2}{9{\cdot}81} = \mathrm{a}.$$

Then the turning moment required to give an angular acceleration, $\ddot{\alpha}$ is $\mathrm{a}\ddot{\alpha}$. The natural frequency f_s of the phase-swing is then

$$f_s = \frac{1}{2\pi}\sqrt{\frac{c}{\mathrm{a}}},$$

and the natural period of the phase-swing is the reciprocal of this,

$$T_s = 2\pi\sqrt{\frac{\mathrm{a}}{c}}.$$

In practice we find that there are forces tending to damp the swing. The damping forces can be increased by providing the poles of the machine with amortisseurs or dampers. The damping forces * are almost proportional to the velocity of the swing, so that we may write:

Damping torque $= b\dot{\alpha}$ kilograms at a metre,

where $\dot{\alpha}$ is the velocity of phase-swing of the rotating part. If the rotating part is displaced from the synchronous position and then released, there being no disturbing forces on the rotating part, we have

$$\mathrm{a}\ddot{\alpha} + b\dot{\alpha} + c\alpha = 0. \quad \text{(1)}$$

From which we get

$$\alpha = \epsilon^{-\frac{b}{2\mathrm{a}}t}\left\{C_1\epsilon^{\frac{\sqrt{b^2-4\mathrm{a}c}}{2\mathrm{a}}t} + C_2\epsilon^{-\frac{\sqrt{b^2-4\mathrm{a}c}}{2\mathrm{a}}t}\right\}. \quad \text{(2)}$$

* For the method of calculating the damping forces from the dimensions of the amortisseur, see *Specification and Design of Dynamo-Electric Machinery*, p. 354.

If b^2 is negligibly small in comparison with $4ac$, we have, approximately,

$$\alpha = \epsilon^{-\frac{b}{2a}t}\left\{M \sin\sqrt{\frac{c}{a}}\,t + N\cos\sqrt{\frac{c}{a}}\,t\right\}, \quad \text{......................(3)}$$

where M and N are constants that depend upon the amplitude and phase of the original displacement.

EXAMPLE. Take a 1000-K.W. generator * running at 200 R.P.M., having a flywheel capacity of 262 tons at a foot radius². Then

$$a = \frac{262 \times 94{\cdot}4}{9{\cdot}81} = 2520 \text{ in kilogram-metre units.}$$

Let the constant c, by which we multiply α in order to get the synchronizing torque, be equal to 224,000. Let the damping force when $\dot{\alpha}$ is one radian per second be 4000. If the field-magnet is displaced from the synchronous position and then released, we have the equation

$$2520\ddot{\alpha} + 4000\dot{\alpha} + 224{,}000\alpha = 0.$$

The value of $4ac$ in equation (1) on page 228 is

$$4 \times 2520 \times 224{,}000 = 2{\cdot}3 \times 10^9,$$

and b^2 is only $1{\cdot}6 \times 10^7$, or less than 1 per cent. of $4ac$. Therefore we have approximately, from (3),

$$\alpha = \epsilon^{-{\cdot}794t}\{M \sin 2\pi 1{\cdot}5t + N \cos 2\pi 1{\cdot}5t\}, \quad \text{.............................(4)}$$

$$f_s = \frac{1}{2\pi}\sqrt{\frac{224000}{2520}} = \frac{9{\cdot}43}{6{\cdot}28} = 1{\cdot}5 \text{ cycles per second.}$$

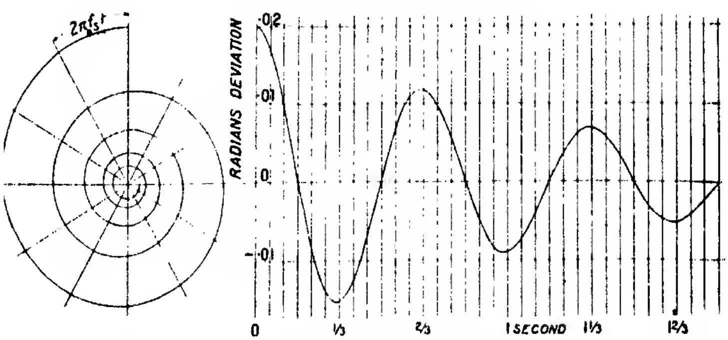


FIG. 224.—Damped phase-swing of 1000 K.W. generator when full load is suddenly switched off.

When $t=0$, let $\alpha = {\cdot}02$ radian and $\dot{\alpha} = 0$. If the generator were running at full load with an angular displacement of the field magnet of 13·75 electrical degrees, this would correspond on a 24-pole machine to $\alpha = {\cdot}02$ radian. If at the instant $t=0$ the load is switched off the field magnet will return to its no-load position, but only after exhibiting the damped phase-swinging as shown in Fig. 224. Putting $t=0$ in (4), we get

$${\cdot}02 = N.$$

Differentiating (4) and equating to zero, we get

$$M = {\cdot}00168.$$

Therefore $\qquad \alpha = \epsilon^{-{\cdot}794t}\{{\cdot}00168 \sin 2\pi 1{\cdot}5t + {\cdot}02 \cos 2\pi 1{\cdot}5t\}.$

* See page 218 for particulars of turning moment of engine driving such a generator, and page 220 as to constants for converting from British units into metric units.

The easiest way of plotting an expression like this is to calculate the values of $\epsilon^{-7.94t}$ and set them out as radii, making successive angles $2\pi f_s t$ with the vertical line, as shown in Fig. 224. In this way we obtain a logarithmic spiral, as shown on the left of the figure. Then choosing a suitable time-scale and erecting ordinates that correspond in time with the successive radii, it is an easy matter to project points on the spiral on to the corresponding ordinates. This gives the damped sinusoidal curve on the right of the figure. The scale of the ordinates can be adjusted to make the first ordinate equal to the initial displacement of the magnet (in this case ·02 radian).

Forced vibration. Next, consider the case where the engine has an irregular turning moment. The simplest case is where a disturbing torque $Q_d \sin 2\pi f_d t$ is superimposed upon the uniform torque demanded by the load. In practice the disturbing torque is much more complex, as was seen in Fig. 215; but it is best to take the simple case first, and afterwards we can see how the matter is affected by the introduction of higher harmonics into the disturbing torque. As the uniform torque is supposed to be absorbed by the load, the disturbing torque is the only turning moment other than the three turning moments given in equation (1), page 228. Thus we have

$$a\ddot{\alpha}+b\dot{\alpha}+c\alpha=Q_d \sin 2\pi f_d t, \quad \ldots\ldots\ldots\ldots(5)$$

where a, b and c are the constants considered on page 228, and f_d is the frequency of the disturbance. Writing

$$2\pi f_d=\omega \quad \text{and} \quad (a\omega^2-c)=k,$$

we have

$$\alpha=-\frac{Q_d}{\sqrt{\omega^2 b^2+k^2}}\sin\left(\omega t+\tan^{-1}\frac{\omega b}{k}\right). \quad \ldots\ldots\ldots\ldots(6)$$

If it should happen that a and c have such values that $a\omega^2=c$, then $k=0$. This is the condition of resonance; for we have seen that the natural period of phase-swing

$$f_s=\frac{1}{2\pi}\sqrt{\frac{c}{a}}; \quad a4\pi^2 f_s^2=c=a\omega^2=a4\pi^2 f_d^2.$$

Therefore, under these conditions, $f_s=f_d$.

If $k=0$ and the damping constant b is very small, α may be exceedingly great, because the divisor in (6) is very small. Thus a very small disturbing torque can bring about a very troublesome phase-swing if its frequency is equal to the natural period of swing and the damping forces are small.

If $a\omega^2$ is nearly equal to c, and if b is small, the phase-swing may be excessive. Let us take $b=0$, and write $\frac{c}{a\omega^2}=q$; then the maximum value of α is

$$\frac{Q_d}{k}=\frac{Q_d}{a\omega^2-c}=\frac{Q_d}{a\omega^2(1-q)}. \quad \ldots\ldots\ldots\ldots(7)$$

That is to say, the deviation of the flywheel from the synchronous position is proportional to the disturbing torque and inversely proportional to the flywheel capacity a, to the square of the frequency of the disturbance, and to $(1-q)$.

The final value of the synchronizing torque is

$$Q_{sf}=ca_f=\frac{cQ_d}{a\omega^2(1-q)}=\frac{q}{(1-q)}Q_d.$$

Let $Q_d=m$ times full-load torque, then $Q_{sf}=\frac{q}{(1-q)}\times m$ of full-load torque, and the synchronizing power

$$P_s=\frac{mq}{(1-q)}\text{ of full load.}$$

Thus, if Q_d is 0·5 of full load torque, and $q=0·3$,

$$P_s=\frac{0·5\times0·3}{0·7}=0·214\text{ times full load.}$$

That is to say, the reading of the wattmeter will oscillate between two points, one of which is 21·4 per cent. of full load above the mean and the other 21·4 per cent. of full load below the mean reading.

When $a\omega^2$ is nearly equal to c, q is nearly equal to 1, so that the value of (7) becomes great. It is therefore always desirable to avoid a flywheel that gives such a value of a as to make $a\omega^2$ nearly equal to c. From the fact that ω^2 comes in the denominator, we see that a disturbing torque of low frequency is much more likely to cause trouble than a disturbance of high frequency. If there are a number of disturbing torques of different frequencies superimposed, q will have a different value for each frequency. If the flywheel is of such a capacity as to make $q=1$ or nearly 1 for any particular frequency, the deviation caused by the disturbing torque of that frequency will be increased by resonance. When the torque curve is an irregular one, like that shown in Fig. 215, it can be broken up by harmonic analysis into a number of disturbing torques of different frequencies. In the case where the prime mover is a gas engine, the fundamental of the harmonic series will often be found to have the frequency of the cam-shaft—that is to say, half the frequency of revolution. It may be that the amplitude of the disturbance having this frequency is much smaller than the amplitude of disturbances of higher frequency, and yet its effect in causing a deviation of the flywheel from uniform motion may be much more conspicuous than the effect of disturbances of greater amplitude and higher frequency. This will be especially so if the natural period of phase-swing of the generator is nearly the same as the period of the cam-shaft. For this reason it is of great importance to fix the flywheel effect of the rotating part of a gas-driven A.C. generator so that the natural period of phase-swing does not coincide with the period of

the cam-shaft. How far the periods must differ in order to get good running conditions is considered below (see page 237).

In the case of a steam engine the fundamental frequency is usually the frequency of revolution, and with gas engines too the frequency of revolution must be avoided when fixing the frequency of phase-swing, though when a gas engine works on an Otto cycle it is half the frequency of revolution that is most to be feared. It is common to find that the disturbances of the greatest amplitude have the frequency of the impulses received from successive cylinders. When the engine has several cylinders these impulses have a frequency several times as great as the frequency of revolution, and ω^2 (see page 231) having a fairly high value, the value of α brought about by such disturbances may be quite small notwithstanding the great amplitude of the irregularities in the turning moment. It is of course important to avoid resonance with these impulses.

The adjustment of the frequency of phase-swing. As shown above, when b is small the frequency of phase-swing

$$f_s = \frac{1}{2\pi}\sqrt{\frac{c}{a}}.$$

Both c and a are open to some adjustment when the plant is being designed.

$$c = \frac{EI_u p}{9{\cdot}81 \times R_{ps} \times 2\pi} \text{ kilograms weight at a metre radius.}$$

This is for a single-phase generator. For a three-phase generator

$$c = \frac{1{\cdot}73 EI_u p}{9{\cdot}81 \times R_{ps} \times 2\pi},$$

where E is the voltage between terminals, I_u is the synchronizing current per unit angle of displacement of the field from the synchronous position, and p is the number of pairs of poles.

The fixing of I_u is a matter for the designer of the generator.* It varies with the strength of the field-magnet. It is sufficient to say that in alternators which have a strong field-magnet and weak armature reaction I_u is great; and in alternators having a weak field-magnet and strong armature reaction I_u is small. In machines having a cylindrical field-magnet, like some turbo-generators, I_u for any excitation of the field is just a little greater than the armature short-circuit current for the same excitation of the field-magnet. In machines having salient poles, I_u may be twice as great as the armature short circuit for any given excitation of the field-magnet.

Change of I_u with change of excitation. As the load on a generator is increased the excitation is increased, and the value of I_u is also increased, but not in proportion to the increase of the field current.

* See *Specification and Design of Dynamo-Electric Machinery*, p. 342.

When a 3-phase machine is running on a low power-factor the armature exerts a demagnetizing effect upon the field-magnet, which varies very little with small changes of the angle σ. Thus it comes about that when the field current passing through the magnet windings is increased, in order to compensate for the demagnetizing effect of a load at low power-factor, the increased excitation has not as much effect in increasing I_u as an increase of excitation which, being made at unity power-factor, brings about an increase in the terminal voltage. Nevertheless the increase of excitation at low power-factors, in so far as it brings about an increase in the *generated* voltage and calls for more ampere-turns on the air-gap and armature teeth, does increase somewhat the value of I_u, so that the natural frequency of swing changes with the load. In cases where the operating conditions call for a wide range in the generated voltage, the value of c changes in proportion to EI_u and the frequency of swing changes as the square root of this product. Thus a generator may, during the hours of light load on the power-station, be operated at 6300 volts, and during the time of heavy load the voltage on the busbars may be 6600, and the generated voltage 6900 (the extra 300 volts being consumed on the impedance of the winding). Let us suppose that at light load the value of I_u is 3 times full-load current, and at full load I_u is 3·5 times full-load current; the value of EI_u would change in the ratio of 6300×3 to $6600 \times 3·5$ or 1 to 1·22, and the natural frequency of swing would be increased 10 per cent. under the full-load conditions.

This variation of frequency of phase-swing under operating conditions makes the risk of resonance with some one or other of the periodic impulses of the engine much greater than it otherwise would be. When the average frequency of phase-swing is adjusted so as to lie between two dangerous frequencies (say the frequency of the cam-shaft and the frequency of revolution of a gas engine), a change in the operating conditions may at times bring the machine dangerously near resonance with either the upper or the lower frequency.

Let us take the case of a gas engine (having an Otto cycle) running at 200 revs. per minute (or 3·33 revs. per sec.). Then the frequency of the cam-shaft is 100 per minute (or 1·66 per second). The two dangerous frequencies to be avoided in fixing the natural frequency of phase-swing are 1·66 and 3·33. If one could have unlimited fly-wheel capacity one would of course make the moment of inertia so great as to decrease the natural period of phase-swing considerably below 1·66, and thus remove it from both dangerous frequencies. But to do this sometimes calls for a greater flywheel than the engine-builder cares to put on his bearings. In these cases it may be necessary to make a compromise and choose a flywheel effect which

will give a natural frequency of phase-swing somewhere in between the 1·66 and the 3·33, and yet sufficiently removed from both of them. In choosing the best flywheel effect one must have regard to the amplitude of the disturbing torque which may be expected at each frequency, and at the same time take account of the change in the value of the factor $\frac{q}{1-q}$ (see page 231), by which we must multiply the disturbing torque in order to find the synchronizing torque. Let us assume at first that the disturbing torque at frequency 1·66 is 0·05 of full-load torque, and that the disturbing torque at 3·33 cycles is 0·1 of full-load torque.

Taking the constants of the machine from page 229, we have

$$c = 224{,}000,$$

$$\omega_1 = 1{\cdot}66 \times 2\pi = 10{\cdot}45 \quad \text{and} \quad \omega_1^2 = 109,$$

$$\omega_2 = 3{\cdot}33 \times 2\pi = 20{\cdot}9 \quad \text{and} \quad \omega_2^2 = 436.$$

The critical flywheel effect for ω_1 is obtained from the formula

$$q_1 = 1 = \frac{c}{a\omega_1^2} = \frac{224000}{a \times 109}.$$

Therefore $a_{1\,\text{crit}} = 2050$, which means that the flywheel effect is

$$9{\cdot}81 \times 2050 = 20100 \text{ kg. metre}^2.$$

Similarly $a_{2\,\text{crit}} = \frac{22400}{436} = 512$ (= flywheel effect of 5020 kg. metre²).

If we choose a flywheel so that $a = 1025$, we shall get

$$q_1 = \frac{224000}{1025 \times 109} = 2,$$

so that the synchronizing power which will show itself in the swinging of the wattmeter will be

$$P_{s1} = \frac{m_1 \times q_1}{(1-q_1)} = \frac{0{\cdot}05 \times 2}{1-2} = -0{\cdot}1 \text{ of full-load watts.}$$

If we take the full load of the generator at 1000 K.W., the wattmeter will swing over a range from 900 K.W. to 1100 K.W., the period of swing being 1·66 seconds. Now, considering the disturbance at the higher frequency 3·33, we have

$$q_2 = \frac{224000}{1025 \times 436} = \frac{1}{2}.$$

$$P_{s2} = \frac{m_2 \times q_2}{(1-q_2)} = \frac{0{\cdot}1 \times \frac{1}{2}}{1-\frac{1}{2}} = +0{\cdot}1 \text{ of full-load watts.}$$

Superimposed upon the slower swing of the wattmeter needle there will be a swing having a frequency of 3·33, also having an amplitude of 100 K.W.

If, however, the irregularities at each frequency are expected to be of equal amplitudes, say 10 per cent. of full-load torque, it is better to adopt a lighter flywheel so as to remove the frequency of the phase-swing still further from 1·66. It is seen that for a given flywheel effect $q_1 = 4q_2$, so that to find the values which will give us the best intermediate point we can write

$$\frac{x}{1-x} = -\frac{4x}{1-4x}.$$

This gives us $\qquad x = 0·625.$

We should therefore make $q_2 = 0·625$ and $q_1 = 2·5.$

$$a = \frac{224000}{109 \times 2·5} = 825.$$

$$825 \times 9·81 = 8100 \text{ kg. metre}^2.$$

This then is the best flywheel effect under the prescribed conditions, provided always that the engine-builder finds it sufficient to keep down the angular irregularity. If it is not sufficient, then a much heavier wheel should be chosen which will make the frequency of the phase-swing substantially less than 1·66.

The engine-builder as a rule takes no account of the amplification of the phase-swing by resonance. He will give you the deviation in mechanical degrees which he is prepared to guarantee with the generator running on a dead load; but without taking into account the amplifying factor it is impossible to arrive at the best flywheel effect to employ.

Curves like those given in Fig. 225 are of great assistance in fixing upon the size of flywheel. They have been plotted to fit the constants of the 1000 K.W. generator driven by the gas engine, particulars of which are given on page 220. The excitation of the machine is supposed to be fixed at such an amount as to make the critical flywheel effect 262 tons at a foot radius². This flywheel will have four million foot-lbs. of stored energy when running at 200 R.P.M. The value of c at this excitation will be 274,500. From the formulae given on page 230 we can work out the values of q for different flywheels and thus arrive at the values of $\frac{q}{1-q}$. These are plotted as shown in Fig. 225. We must next decide upon what we regard as the maximum permissible swing of the wattmeter. In the example worked out this is fixed at one-eighth of full-load deflection. The disturbing torque (of fundamental frequency) as worked out by the engine-builder may be expressed as mQ_t, where Q_t is full-load torque and m is a numerical coefficient. From page 231 we have the synchronizing power,

$$P_s = \frac{mq}{1-q} \text{ full load.}$$

If, therefore, we divide 0·125 by $\frac{q}{1-q}$ for each value of flywheel effect, we get the highest permissible value of m, which will ensure that the oscillating watts do not exceed one-eighth of the full-load watts. The values of the permissible m plotted in this way lie on a straight line, because the values of $\frac{q}{1-q}$ form a rectangular hyperbola.

When the engine-builder is provided with a diagram of this kind by the maker of the generator, all he has to do is to work out what he

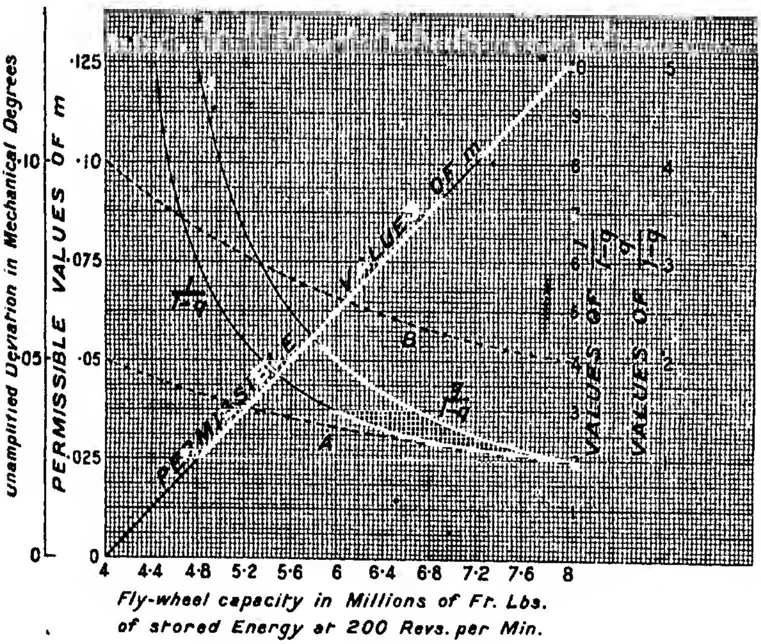


FIG. 225.

expects to be the disturbing torque having the fundamental frequency, and from the diagram he reads off the flywheel required. For instance, in our present case, if the disturbing torque having a frequency of 1·66 was expected to be 2200 lbs. at a ft. radius, this would be $\frac{2200}{35500}$ = ·0325 of full-load torque. Therefore m = ·0625. Referring to the diagram we see that the flywheel required would be a six-million ft.-lb. flywheel. If the disturbing torque had worked out at 3550 lbs. at a foot we would have m = 0·1, and this would require a 7·2-million ft.-lb. wheel. It is convenient to also have plotted curves like those shown at A and B, which give the unamplified deviation of the flywheel for different values of m. Curve A gives the deviation of

the flywheel for $m=0{\cdot}05$, and curve B the deviation for $m=0{\cdot}1$ when the generator is running on a dead load. In order to get the actual deviation as amplified by the phase-swing it is necessary to multiply by $\dfrac{1}{1-q}$. The values of $\dfrac{1}{1-q}$ are also plotted on Fig. 225.

In the above no account has been taken of the damping action of the amortisseur or eddy-currents in the pole-faces. It is always well to fix the flywheel effect independently of the damping action where this is at all possible. Sometimes, however (especially in the case of turbo-machines which are to be run in parallel with reciprocating sets) there is great difficulty in adjusting the flywheel to the best value, and one must rely to a very great extent on a good amortisseur to keep down phase-swinging.

Amortisseurs may be described according to their effectiveness as "one-per-cent." dampers or "two-per-cent." dampers, as the case may be. A one-per-cent. damper is a squirrel cage on the field system, which would, if the generator were run as an induction motor, enable the motor to yield full-load output with a slip of one per cent. A two-per-cent. damper would require a slip of two per cent. before the motor took full load.

In order to take the damping into account we make use of formula (6) on page 230. The value of b can be calculated as follows:

$$b=\frac{\text{Full-load watts}\times p}{9{\cdot}81\times R_{pu}\times 4\pi^2\times f\times s},$$

where f is the frequency of the alternator and s the slip that the damper would give on full load.

Two examples will be sufficient to show the application of the formulae.

First take the case where there is perfect resonance and a one-per-cent. damper,

$$a=2520,\quad a\omega^2=274{,}500,\quad c=274{,}500,\quad a\omega^2-c=0,$$

$$\alpha=\frac{Q_d}{\omega b},$$

$$b=\frac{1000000\times 12}{9{\cdot}81\times 3{\cdot}33\times 4\pi^2\times 40\times 0{\cdot}01}=1{\cdot}54\times 10^4,$$

$$\omega b=1{\cdot}61\times 10^5.\quad \text{Take } Q_d=487 \text{ kg. metres.}$$

Then $\alpha=\dfrac{487}{1{\cdot}61\times 10^5}=0{\cdot}00303$ radian (mech.), $=0{\cdot}00303\times 12\times 57{\cdot}3=2{\cdot}1^\circ$ (elect.).

Or, to get the synchronizing torque,

$$0{\cdot}00303\times 274500=830 \text{ kg. at a metre},$$

$$\frac{830}{4870}=0{\cdot}17 \text{ of full-load torque.}$$

That is to say, a one-per-cent. damper can keep down the oscillating watts to 17 per cent. of full-load watts even when the flywheel effect is such as to give complete resonance.

Next increase the flywheel effect by 50 per cent., so that a = 3780.

$$a\omega^2 = 412000$$
$$c = 274500$$
$$k = (a\omega^2 - c) = 137500$$

$$a = \frac{Q_a}{\sqrt{\omega^2 b^2 + k^2}} = \frac{487}{10^5\sqrt{1\cdot61^2 + 1\cdot375^2}} = 0\cdot00232,$$

$$0\cdot00232 \times 274500 = 637 \text{ kg. at a metre},$$

$$\frac{637}{4870} = 13 \text{ per cent. of full-load power.}$$

Thus it is seen that when there is a fairly good damper the increasing of the flywheel effect even by as much as 50 per cent. does not greatly reduce the phase-swing. This is because the flywheel effect and the damping effect operate at right angles to one another.

Method of procedure. The trouble met with in the synchronous running of A.C. generators presents itself in various ways. The simplest case occurs when there are only two generators connected to the busbars and these are similar and driven by similar engines. In this case the theory given above is directly applicable, as it is not difficult to find the cause of the phase-swinging. The first step is to find the frequency of the phase-swing. This can generally be taken with sufficient accuracy from the swing of the wattmeter needle. After the second machine has been synchronized and switched in parallel, the wattmeter may begin to swing; and it usually makes a good many swings before it goes hard over and the breakers come out. It is usually possible to find a state of excitation at which the generators will run long enough in parallel to enable the frequency of the phase-swing to be observed. The movements of the wattmeter needle require to be rather closely studied, because they may be made up of several vibrations of different frequencies superimposed. The natural period of swing of the wattmeter itself may be such as to very much accentuate an impressed vibration of nearly the same period, although this particular vibration is of much less importance in the problem than the principal oscillation of power between the machines. It is a good plan to put in circuit another wattmeter having a different period of swing. The series transformer used in conjunction with the wattmeter should be chosen so as to give only a small deflection on full load. If the pointer during the phase-swing bounces against the zero stop, the position of the pointer can be changed either on the zero adjustment or by the addition of a small D.C. load fed

from an accumulator and a rheostat. By watching two wattmeters of different natural periods of swing, it is possible to recognize the main swinging of the phase and to count the number of swings per minute. This will nearly always be found to bear some simple relation to the number of revolutions per minute of the prime mover. In the case of a gas engine working on an Otto cycle, there will generally be found one phase-swing for two revolutions of the engine. An ordinary steam engine generally causes one phase-swing per revolution. An engine provided with a single-acting condenser pump may have its speed so affected by the pump as to cause one phase-swing for every stroke of the pump.

Other periodic disturbances have been known to set the time for the phase-swing. In the case of steam turbines and steam engines, it is possible for the governor to hunt in a perfectly periodic manner; and if the flywheel of the set just happens to give a frequency of phase-swing that accords with the period of the governor, the two actions may play into one another's hands in a manner that makes running impossible until the adjustments have been altered. It is an easy matter to find out whether this is happening. The automatic action of the governor can be suspended for the time being, and the governing can be done by hand. If this stops the phase-swinging, the natural period of hunting of the governor should be altered so as to be as far removed as is convenient from the natural period of phase-swing. In the case of very large gas engines such as are used for obtaining power from coke-oven gas, where the gas is fed along large pipes of considerable length, it is possible for a wave-motion to be set up in the feed-pipe such as to affect the strength of mixture of air and gas according to a periodic law, and it is possible that the period of this may cause resonance with the period of phase-swing. It can be seen, therefore, that the first step is to find out the frequency of the important phase-swing, and the next is to find something in the action of the engine that has the same frequency. It then remains to diminish the irregularity in the engine as much as possible, and to alter its period. If the latter cannot be done, then the period of phase-swing of the generator must be altered either by changing the flywheel or by changing the ratio of field ampere-turns to armature ampere-turns. If neither of these can be altered without very great expense, then the addition of a good amortisseur to the poles may be effective in cases where the disturbing force is not too great. The cases worked out on p. 237 show quantitatively how far a damper can be relied upon to cut down the amplitude of the phase-swing.

A recording wattmeter, with a drum running fast enough to give good records of the variation in the watts, is quite a useful instrument to have. The damping of the needle by the friction on the

paper is fairly effective; and as one does not usually require results which give the amplitude with great accuracy, the damping should be encouraged.

The tachograph is of very great service in making a record of the change of speed of the engine and throwing light on the cause of bad synchronous running. It is in general more difficult to get and to install than a wattmeter. For this reason, the author recommends an investigation to see whether sufficient information cannot be obtained from the wattmeter before the expense of getting a tachometer is incurred. It should be noted that the tachometer shows the change of speed, whereas the wattmeter shows the displacement of the generator field-magnet from the synchronous position. As the displacement is the time integral of the speed, an effect which is not very conspicuous upon the speed curve may be quite important when the amount of the displacement it produces is revealed. Before a tachometer is installed, the generating set should be inspected to see what part of the shaft or other cylindrical surface can be used for driving the belt of the tachometer. Sometimes in very slow speed sets it is necessary to attach a special wheel on the end of the shaft in order to get a suitable drive. A little forethought and enquiry as to the means of driving the tachometer at its proper speed will sometimes save time in the actual test. Some tachometers are provided with a device for making a small prick in the paper at each revolution of the engine: where this device is used, a very complete record should be kept of the position of the various cranks of the engine at the instant when the prick is made in the paper. In the case of the gas engine, it is best to record the position of the cam-shaft when the prick is made, and to arrange the electrical contact on the cam-shaft instead of on the main shaft. The engine-builder is then able to determine to which particular cylinder, or to what particular action of the parts, the irregularity that is most to be feared is due. Having exact knowledge, he is in a better position to remedy the defect. It would be useful to arrange for this pricking device on a recording wattmeter.

Sometimes an **oscillograph** is used to determine more exactly the instantaneous changes in the current and its phase relations to the voltage. If a kinematograph strip is employed to take a record of current and voltage throughout a complete phase-swing, very interesting results are revealed, which are of great value in the study of synchronous running; but in most cases it is sufficient to determine the frequency of the phase-swing and to get a rough idea of how the amplitude varies (*a*) with the load, and (*b*) with the excitation. For these purposes an ordinary wattmeter is usually sufficient. In the above we have considered the simple case of two similar generators driven by similar engines. Where the engines

are not similar, and where they run at different speeds, the method of procedure is the same, but there will be a greater number of possible frequencies of disturbance, and it may therefore be more difficult to find a suitable flywheel. In cases where it is found difficult to run the sets in parallel for a period of time long enough to make satisfactory observations, it is a good plan to reduce the voltage to about one-half. This has the same effect upon the natural period of phase-swing as increasing the flywheel. Sets which will not run for half a minute in parallel at full voltage will sometimes run reasonably well at half voltage. The phase-swinging, however, is generally very apparent, and its frequency can be noted as the excitation is gradually increased. In this way experiments can be made to ascertain what would be the effect of increasing the flywheel effect. If it is found that a machine can be made to run well at a reduced voltage, we may be sure that it will run as well or better with the flywheel increased so as to give the same natural period of swing at full excitation; because under the latter condition the synchronizing force will be greater, so that the disturbing force will be less in proportion.

A generator running in parallel with busbars fed by a number of generators may work badly on account of the irregular turning moment of some one of the other generators. In this case the frequency of swing may not bear any simple relation to the speed of the engine. The method of procedure is the same as in the case considered above. Having found the frequency of the phase-swing, it is not difficult to find which engine is causing the disturbance. When several generating sets connected to the busbars have the same speed, observations can be made of the effect of shutting down each set in succession while the others are running.

The cause of the disturbance having been ascertained, everything should be done to reduce it to a minimum by a better setting of the valves or by other methods which will occur to the makers of the prime mover. If, then, in addition the constants of the generator (see page 228) and the flywheel effect are altered so as to remove the natural period of swing as far as possible from the period of the disturbance, it will generally be found that parallel running becomes possible and the actual swing of the wattmeter does not exceed the value obtained by calculation according to the method described on page 230.

Destruction of armature winding on short circuit.

If a short circuit occurs on the armature winding of a generator when it is running fully excited, the instantaneous current that flows is only limited by the impedance of the winding. If the impedance is very low, as is often the case in large turbo-generators, the instan-

taneous value of the current may be enormous and may set up magnetic forces so great as to distort the winding and destroy the insulation. The laws governing the flow of current in such cases, and the means to be taken to brace the winding so that it may resist the great magnetic forces, are dealt with * in books on design.

In cases where it is impossible to make any further improvements in the design of the generators, the rush of current on short circuit may be reduced by connecting choke coils in series with the armature. These choke coils † must be designed so that their magnetic circuits do not become saturated when the maximum current is flowing, otherwise the current may increase a long way beyond the calculated point. The usual practice is to make the cores of the choke coils of a material that is not paramagnetic, such as air, concrete or porcelain. If then the reactance drop in the choke coil and armature at full load is 10 per cent. of the supply voltage, it is impossible for its current to rise to a greater value than 10 times full-load value on short circuit.

Other defects occurring in A.C. generators have already been dealt with under the following headings: Low Efficiency (page 69), Abnormal Temperature Rise (page 41), Insulation Breakdown (page 10), Noise (page 150).

* See *Specification and Design of Dynamo-Electric Machinery*, p. 125.

† See Faye-Hansen and Peck, *Journ. I.E.E.*, vol. 53, p. 511, 1914.

CHAPTER VII.

REGULATION OF DIRECT-CURRENT GENERATORS.

I. SHUNT-WOUND GENERATORS.

SHUNT-WOUND direct-current generators are sometimes guaranteed not to drop in voltage by more than a specified amount between no-load and full load. When the generator is sold in combination with a direct-connected engine, the guarantee figures generally take into account the change in speed in the engine. When the prime mover comes under a separate contract, the regulation guarantee relating to the generator is based on the assumption that the speed is constant, or on an assumed drop in speed of the engine, say 2 per cent., between no-load and full load. This drop in speed of the engine is a very important factor in the regulation of a shunt-wound combined set; because, apart from any compensating influences such as are considered below, a drop in speed of a certain percentage will lead to a drop in voltage of a greater percentage, owing to the fall in the shunt excitation at the same time. It is therefore very important when enquiring into the behaviour of a combined set in this respect to see how far the prime mover is complying with the terms of the contract. It not infrequently happens that when the engine governor is properly adjusted the combined set can be made to meet its guarantee.

The effect of change in speed on the no-load voltage of a shunt generator is most easily studied by means of a number of magnetization curves plotted for different speeds. If the no-load magnetization curve giving the relation between field amperes and volts generated is taken at any given speed, it is easy to derive the curves for any other speed by the simple expedient of changing the ordinates in proportion to the speed. Fig. 230 gives a number of magnetization curves of a shunt-wound generator plotted for different speeds. If now a number of straight lines are drawn sloping upwards from the origin, as shown in the figure, each of these lines gives the relation between voltage and current in a field circuit having a given

resistance. For instance, the line marked 80 ohms cuts the 500 R.P.M. curve at a point where the voltage is 300 and the field current is 3·75 amperes. It cuts the 600 R.P.M. curve where the voltage is 455 and the current is 5·69, and the 700 R.P.M. curve where the voltage is 582 and the current is 7·271, the volts divided by the amperes

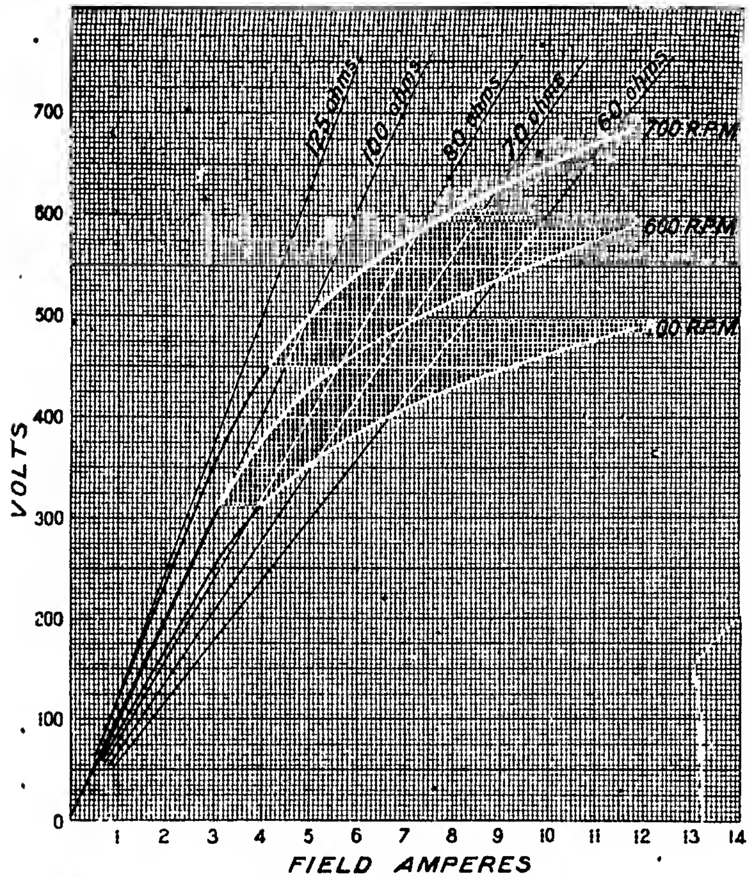


FIG. 230.—Magnetization curves at various speeds, showing intersection of lines representing the shunt resistance.

being in each case 80 ohms. Similarly the 70-ohm line gives at each point of intersection a ratio of volts to amperes equal to 70. It is clear that if the rheostat in the shunt circuit is adjusted so as to make the total resistance in that circuit equal to 80 ohms, the machine, when running at 500 R.P.M., 600 R.P.M. and 700 R.P.M., will generate 300 volts, 455 volts and 582 volts respectively. Such

a diagram enables us to find at once the voltage at any speed for any resistance in the shunt circuit.

If we wish to find the effect on a generated voltage of small changes of speed, it is best to plot a portion of the curves on a larger scale, as shown in Fig. 231. Here the central curve is part of the magnetization curve at 600 R.P.M., and the other curves give the characteristic for speeds differing by 1 per cent., 2 per cent. and 3 per cent. We see that if the resistance of the shunt circuit is

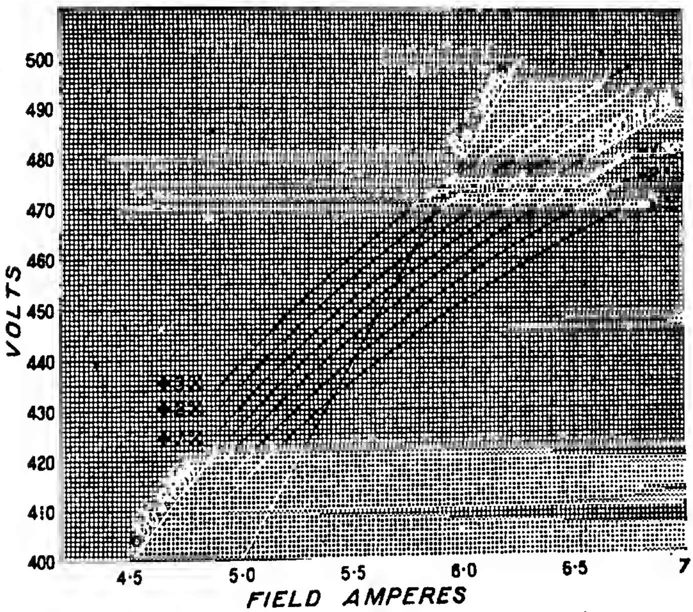


FIG. 231.—Magnetization curves for small changes in speed showing the intersections with line representing 80 ohms in the shunt circuit.

80 ohms, a drop in speed of $1\frac{1}{2}$ per cent. from 600 R.P.M. will cause a drop in the voltage from 455 to 443·6, the difference being $2\frac{1}{2}$ per cent. If the shunt resistance is lower and the voltage is higher for any given speed, the saturation of the magnetization curve being greater, the magnetization curve more nearly approaches the horizontal. When the saturation is greater, the percentage change of voltage is more nearly equal to the percentage change of speed. At lower saturations, and particularly at points below the knee where the magnetization curve becomes more nearly straight, very small changes in speed create much greater changes in voltage. If the straight line representing the shunt resistance nearly coincides with the straight part of the magnetization curve at any given speed,

the generator will be very unstable at that speed and rheostat adjustment; and the voltage will be found to vary over a wide range, owing to small accidental circumstances such as small changes in brush resistance. This would be the state of affairs for a speed of 600 R.P.M. and a rheostat adjustment of 100 ohms (see Fig. 230). If now the rheostat is adjusted so as to give a still higher total

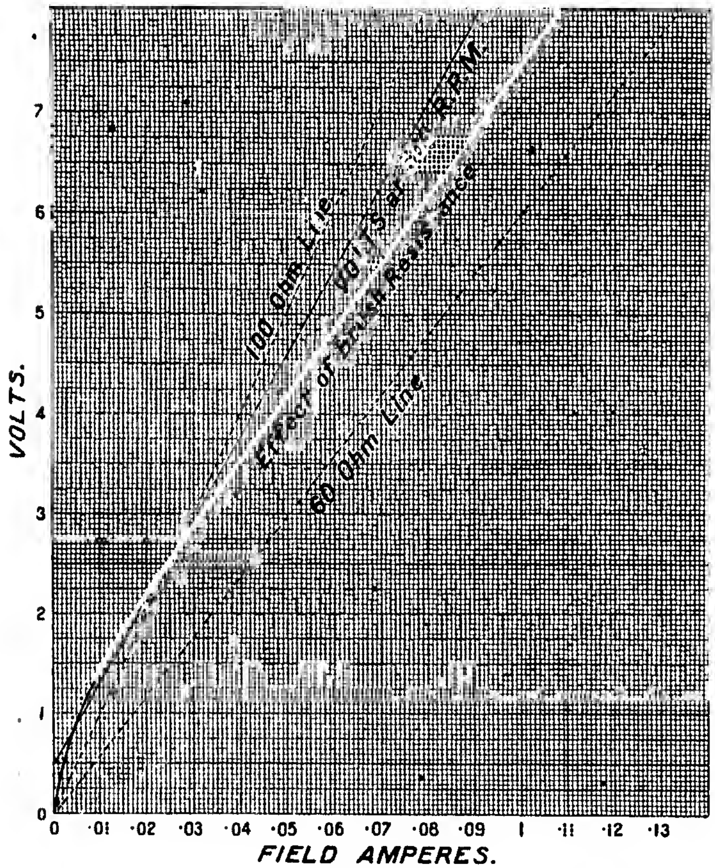


FIG. 232.—Showing the effect of brush resistance at very low excitations.

resistance (say 125 ohms) in the shunt circuit, the machine will not build up at 600 R.P.M., but will only generate a few volts, which are due to residual magnetism assisted by an exceedingly small current through the shunt. This will be the state of affairs when running at 500 R.P.M. if the total shunt resistance is 100 ohms. The conditions when the shunt resistance is too high to allow the generator to build can be understood from Fig. 232. The thin full line

shows the lower end of the 500 R.P.M. magnetization curve plotted to a larger scale. Owing to the residual magnetism in the field circuit, the voltage generated for a zero field current is, say, 0·5 volt at 500 R.P.M. The 60-ohm line and the 100-ohm line are shown dotted in Fig. 232. It will be seen that the 100-ohm line cuts the magnetization curve at 2·7 volts. If, therefore, the resistance of the shunt circuit is 100 ohms, the voltage generated at 500 R.P.M. cannot rise above 2·7 volts, because the 100-ohm line is after that completely above the volt line. If the total resistance of the shunt circuit were 60 ohms, the machine would build up to 403 volts, as seen from Fig. 230. In this connection it is interesting to enquire into the effect of the brush resistance. It is well known that the brush resistance is not constant. When current flows from a carbon brush to the sliding copper surface beneath it, the electrical conducting properties of the materials are altogether different from those obtaining in solid conductors. The conduction appears to take place through an extremely short arc, and a small back E.M.F. exists on the contact surfaces. When the surfaces of the carbon and the copper are very highly polished, this back E.M.F. makes itself evident even down to extremely small current densities, so that when the current passing through the brushes is small the apparent resistance may be extremely high. Where the copper and carbon surfaces are not so highly polished, this back E.M.F. is smaller, and it almost disappears at small current densities. Sometimes it is found that, notwithstanding the fact that the rheostat has been cut out to a point which should enable the generator to build up its voltages at a given speed, the generator refuses to build up even when extra pressure is applied to the brushes. The reason for this will be seen in Fig. 232. It may be that with highly-polished surfaces the combined brush drop of positive and negative brushes is 1·5 volts when the field current is only 0·1 ampere. At the smaller field currents the brush drop is only a little lower; and at 0·01 ampere the brush drop may be as high as 0·4 volt per brush. Thus the effective resistance in the shunt circuit, instead of being represented by the 60-volt line, is represented by the line marked "Effect of brush resistance." This line, starting from zero, cuts the 500 R.P.M. volt line at about 0·83 volt; and under these conditions the machine will not generate more than this voltage, even though the position of the rheostat would lead us to believe that we are working on the 60-ohm line. The easiest way of overcoming this trouble is to put two small pieces of copper wire, one under a positive and one under a negative brush, so as to get a copper-to-copper contact, the voltage drop in which is very much lower.

The explanation of this matter more properly falls under the head "Failure to excite," page 287, but it is disposed of here while

we are dealing with magnetization curves and the effect of resistance in the shunt circuit. It will be seen that the effect of the brush resistance is to slightly increase the slope of the resistance line, even at great excitations, and to increase the slope very greatly at minute excitations.

Shunt generator on load.

When a shunt generator is put on load (assuming that the speed is maintained constant), there are a number of different circumstances which affect the generated voltage. These will be considered under the following headings: (*a*) Armature Resistance, (*b*) Saturation of the Teeth, (*c*) The Position of Brushes, (*d*) The Action of the Commutating Pole, (*e*) The Short-circuit Currents under the Brushes.

(a) **Armature resistance.** Leaving out of account all the other effects, the armature resistance will itself cause a voltage drop equal to $I_a R_a$, where I_a is the armature current and R_a the total resistance of the armature circuit, including series coils on the field magnet. But this will not be the whole drop arising from this cause, because the lower voltage at the terminals of the machine causes a smaller field current to flow, and thus the terminal voltage is still further reduced. If E_l is the voltage generated at full load, we have $E_l - I_a R_a = V$. It must be remembered, however, that the E_l in this formula is not the E.M.F. E_0 generated at no-load, but is the E.M.F. when the exciting current is $\frac{V}{R_s}$, where R_s is the resistance of the shunt circuit. It can be most easily arrived at by referring to a set of magnetization curves such as those given in Fig. 231. Suppose, for instance, that $I_a R_a$ is 1 per cent. of E_0, which we will take to be 455 volts at 600 R.P.M. The 1 per cent. drop due to the armature resistance brings us to the curve below the 600 R.P.M. curve, so that there being 80 ohms in the shunt circuit, the voltage falls to 447·5. Here $E_l = 452$, and from this must be subtracted the 4·5 volts lost in the armature. It will be seen that where the voltage generated is well over the knee of the curve there is not much difference between E_0 and E_l, but where the voltage is below the knee of the curve there may be a very considerable difference.

(b) **Saturation of teeth.** Even when the brushes are exactly on the neutral line, the effect of the armature reaction upon the generated voltage cannot be neglected. The cross-magnetization produced by the armature conductors causes an increased saturation of the armature teeth under the trailing horn of the pole, and by reducing the total area of the field form brings about a very considerable reduction in the generated E.M.F. This matter will be more clearly understood by reference to Fig. 233, which shows by a thin line AA' the shape of the no-load field form of a D.C. generator

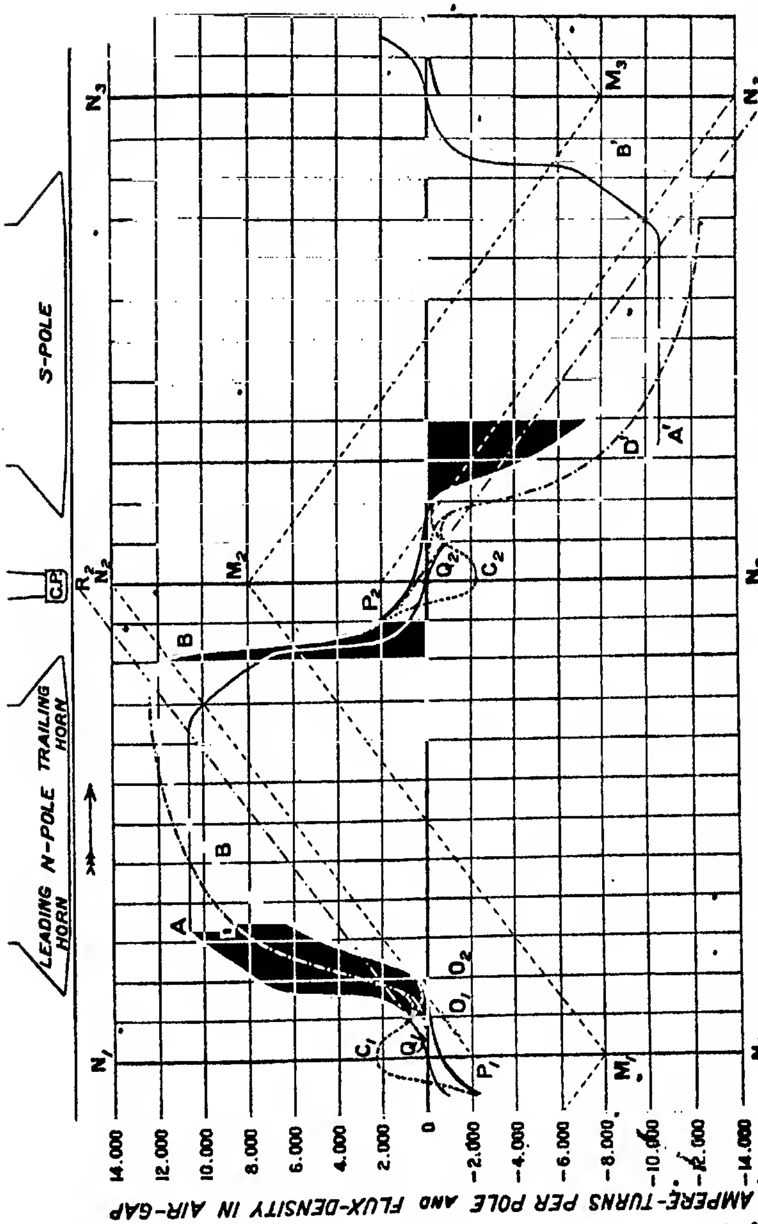


Fig. 233.—Showing the effect of cross-magnetization in lowering the voltage by saturating the teeth.

whose poles are shown diagrammatically above the figure. The magnetomotive force curve of the armature is shown by the line $M_1M_2M_3$. The effect of the armature magnetomotive force is to decrease the flux density under the leading horn of the pole and increase it under the trailing horn. If there were no saturation of the iron, the increase under the trailing horn would exactly balance the decrease under the leading horn, and the total area would be unaltered; but the iron teeth of the armature, which are fairly well saturated at no-load, become supersaturated under the trailing horn, and are not able to have the flux through them increased beyond a certain point. Thus if we take the area of the full-load field form shown by the full line BB' in Fig. 233, we shall see that it is considerably less than the area of the thin no-load field form AA'. The generated voltage being less, the exciting current $\frac{V}{R_s}$ is also less; and the combined effect may be to reduce the voltage by anything from 5 per cent. to 20 per cent. in normal machines.

Fig. 233 has been worked out for a 1000 K.W. 500 volt D.C. generator. The field-magnet has 12 poles, and the armature has a lap winding with 1152 conductors in all. Thus there are 48 turns per pole; and as the armature current per conductor is 167. amperes, the armature ampere-turns per pole are 8000 at full load. The armature M.M.F. curve is then given by $M_1M_2M_3$, which gives a maximum peak of 8000 ampere-turns at the neutral plane N_2N_2, assuming that the brushes are in the neutral position.

We will assume that it requires 6000 ampere-turns per pole at no-load to produce the no-load field form shown by the thin line AA'. If no more shunt ampere-turns than these were applied at full load, the resultant ampere-turns at each point of the air-gap would be given by the dotted lines P_1N_2, P_2N_3. This distribution of M.M.F. would result in the full-load field form shown by the thick full line BB'. The area of this is less than the area of the no-load field form by about 8 per cent. If, however, the field current be increased so that the ampere-turns per pole amount to 7660, the distribution of M.M.F. is then given by the chain-dotted lines Q_1R_2, Q_2R_3, and the field form by the thick chain-dotted curve DD', which has an area 3·6 per cent. greater than that of the no-load field form. By working out curves like BB' for different shunt excitations, we can find by how much the flux is reduced for a given excitation owing to the saturation of the teeth at full load. In order to find the further drop in voltage due to the fall in the excitation, it is necessary to have a magnetization curve giving the relation between the exciting current and the volts generated when the field is subjected to armature distortion. Let curve B in Fig. 234 give this relation for the machine in question. (It can be obtained in practice

by keeping the machine on full-load current and noting the change in voltage as the excitation is varied, and then correcting for the armature resistance drop.)

Curve A in Fig. 234 gives the relation between volts generated and exciting current at no-load. If the resistance of the exciting circuit is 41·3 ohms, the exciting current will be 12·1 amperes and the volts generated 500. When full load is thrown on the machine, even if the excitation remained at 12·1 amperes the generated volts would fall to 460, on account of the distortion and diminution of area of the field form as shown by the thick full line BB' in Fig. 233.

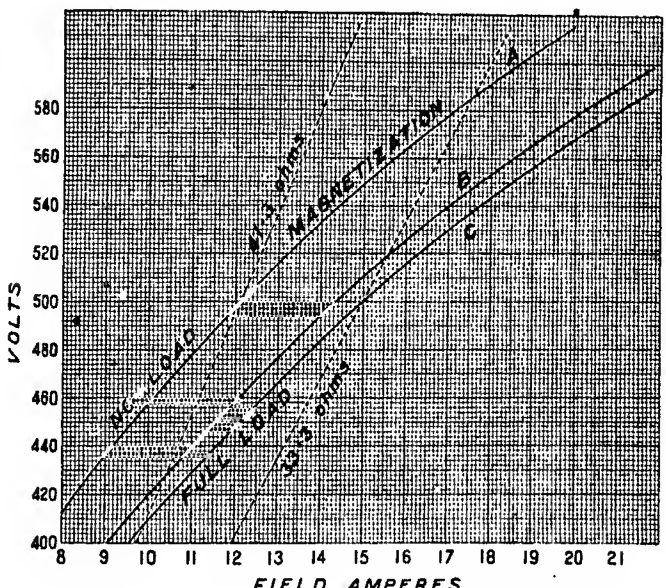


FIG. 234.—Showing the no-load and full-load magnetization curves of a shunt-wound generator.

This brings us on to the B curve in Fig. 234; but the generated voltage will not be 460, for, the excitation voltage being reduced, the exciting current will fall away. To find exactly the point to which the current will fall, we must take into account the armature resistance drop. Suppose the I_aR_a drop is 10 volts; we can draw the curve C 10 volts lower down than the B curve. This is the full-load characteristic of the machine. It is cut by the 41·3-ohm line at a point which gives the exciting current 9·9 amperes and the terminal volts 408. If now it is desired to bring the terminal volts to 500, the excitation must be increased to 15 amperes: that is to say, the resistance of the exciting current must be reduced to 33·3

ohms. We can now draw in the 33·3-ohm resistance line as shown in Fig. 234, and can at once find what will happen if the load is thrown off while the resistance remains at 33·3. The volts will rise to 586 (assuming that the speed remains constant).

As the magnetization curves have a certain amount of curvature, the angles that any resistance line (say the 41·3-ohm line) makes with the curves *A*, *B* and *C* at the point of intersection is not a constant. Therefore the increase in the drop of voltage brought about by the fall in the excitation does not bear a constant ratio to the original drop brought about by any of the causes considered above. Nevertheless, an inspection of the curves enables us to attach a certain value to the percentage increase in the drop due to change of excitation in any particular case. For instance, starting at 500 volts and 12·1 amperes excitation, the distortion of the field causes a drop of 40 volts and the decrease of excitation causes a further drop of 33 volts. That is to say, the voltage drop is increased by 82 per cent. Again, the armature-circuit resistance causes a drop of 10 volts and the decrease in excitation causes a further drop of 8 volts, an increase of 80 per cent.

For any given resistance in the exciting circuit we can plot curves like those shown in Fig. 235. Here curves *s* and *s'* show the drop in voltage due to change of speed as the load comes on. The curve *s* has ordinates proportional to speed. It can be obtained by trial on the set in question, or may be plotted from data relating to the governor of the engine. Curve *s'* takes the fall in excitation into account, and is derived from curves such as those given in Fig. 231.

Curves *a* and *a'* give the drop in voltage due to armature resistance. Curve *a'* takes into account the change in the excitation.

Curves *b* and *b'* give the drop in voltage due to field distortion. Curve *b'* can be found by a load test on the machine, allowances being made for the drop in speed and the effect of the armature resistance. The fact that curves *b* and *b'* have nearly always a very marked curvature is very important when we come to consider the stability of generators and motors running in parallel (see page 371).

The change in voltage at any load can be found by adding together the changes due to each individual cause.

(c) **Position of the brushes.** In order to determine the effect of the brush position on the voltage of a D.C. generator, it is necessary to make a plot of the distribution of potential around the commutator. This has been done for the case of the 1000 K.W. generator, particulars of which are given above, and the curves are given in Fig. 236. The potential of a commutator bar which is midway between the positive and negative brushes when the machine is generating 500 volts at no-load (the brushes being on the neutral)

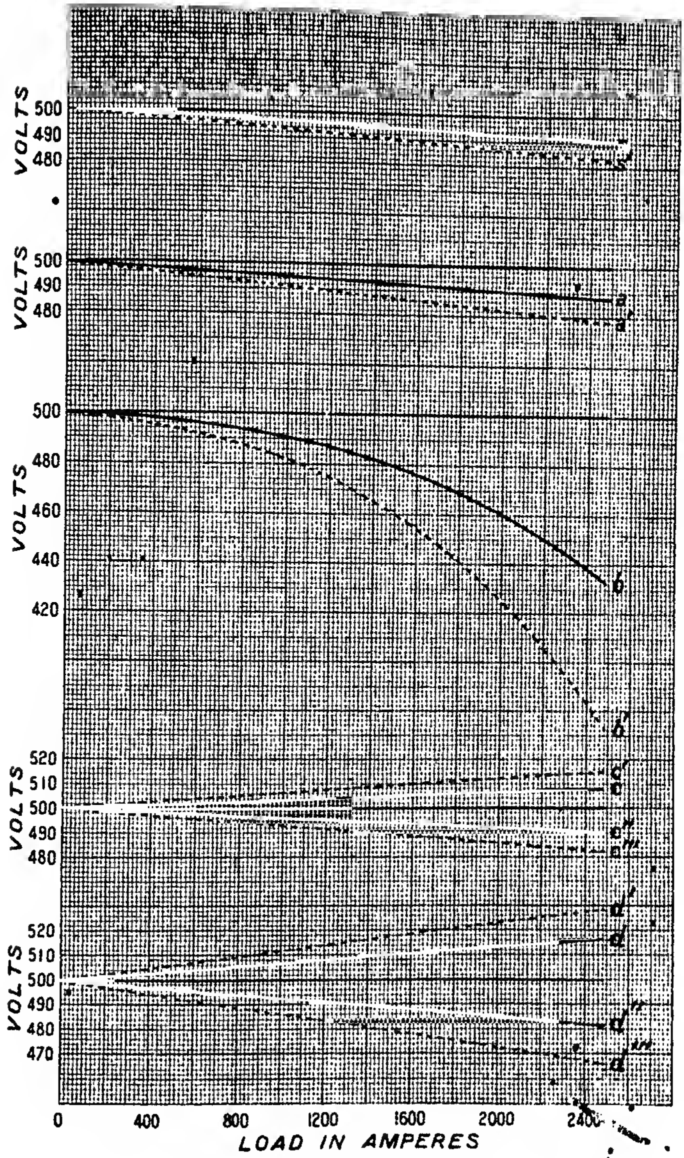


FIG. 235.—Showing the variations in voltage of a shunt-wound generator at various loads due to the causes s, a, b, c and d.

may be taken as the most convenient zero. The positive brush is then 250 volts positive, and the negative brush 250 volts negative. The advantage of this notation will be seen when we come to consider questions relating to commutation. The method of taking the potential curve by measurements on the machine is described on page 282. The potential curve is the integral of the field-form curve, and can be obtained by running around successive sections of the field form with a planimeter and multiplying the readings of the planimeter by a constant, which can be determined as follows:

The curve AA in Fig. 233 gives the no-load field form of the 1000 K.W. generator when generating 500 volts. Take a planimeter and run around the positive loop. Let the reading of the planimeter be V. Then V corresponds to 500 volts. Run the planimeter around a section of curve up to any ordinate 0_1. Let the reading of the planimeter be v_1. Then $\frac{v_1}{V}$ multiplied by 500 is equal to the voltage corresponding to the area of the curve up to ordinate 0_1. The curve AA in Fig. 236 has been plotted in this manner, beginning at the left-hand bottom corner of the positive loop of the A curve, the voltage ordinates being set off from the minus 250 line taken for the time being as zero. As the no-load field form is perfectly symmetrical, it gives a perfectly symmetrical potential curve whose maximum ordinate measured from the temporary zero is 500. This ordinate can now be bisected and a horizontal line drawn through the potential curve, giving a new zero from which we measure 250 volts up to the positive brush and minus 250 down to the negative brush. The machine in question has 48 commutator bars per pole. These bars may be set out along the central horizontal line as shown in Fig. 236. If we wish to obtain the potential curve for any other field form, say for the field form B in Fig. 233, we can take the areas of successive sections as described above, multiply them by the constant to obtain a corresponding voltage, and plot the ordinates so obtained, using any horizontal line as a temporary zero. On the left-hand bottom corner of the positive loop B, at a point where it crosses the zero line, we shall get the point of lowest potential, and we may begin to plot from that point. When the potential curve is complete, the maximum ordinate can be divided by two, a horizontal line being drawn through the point of bisection. The whole curve can then be shifted so that the medial horizontal line falls on the medial horizontal line in Fig. 236, the ordinates 0_1, 0_2, etc., being kept in their original positions. The potential curve obtained in this way from curve B in Fig. 233 is marked BB' in Fig. 233. This curve gives the distribution of potential around the commutator as it would be with a field excitation of 6000 ampere-turns per pole with the armature carrying a full-load current of

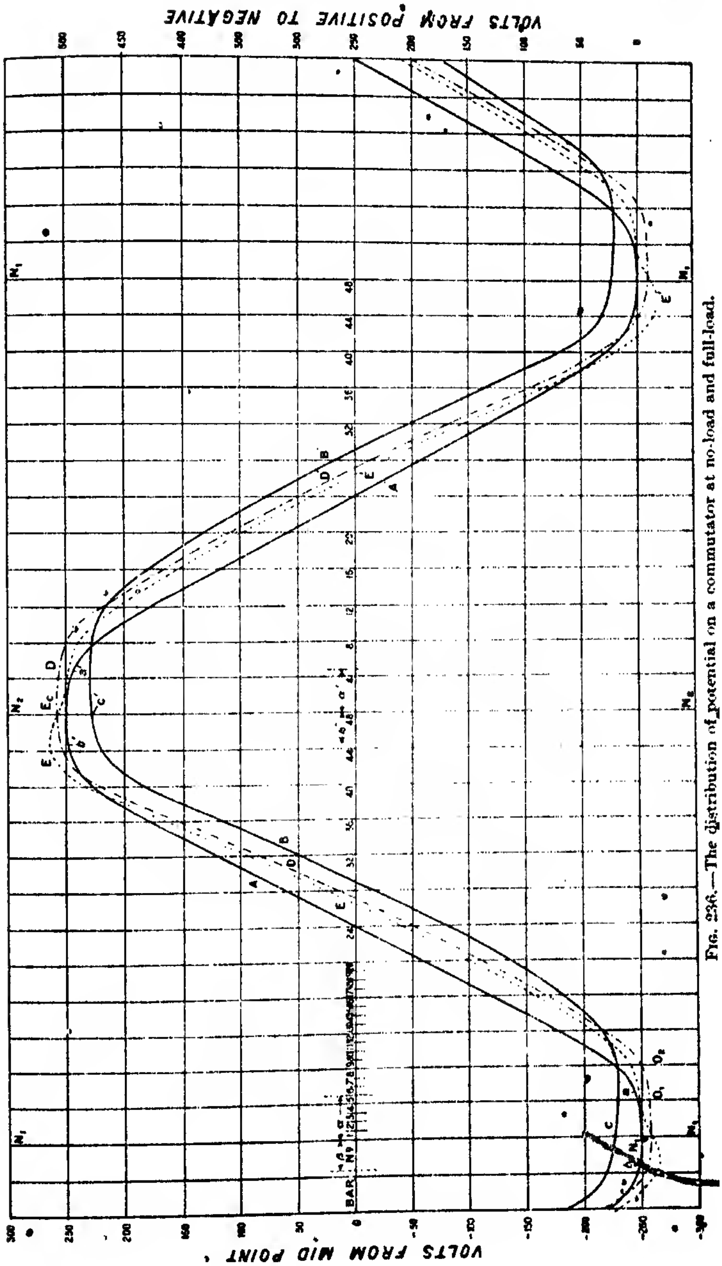


FIG. 236.—The distribution of potential on a commutator at no-load and full-load.

2000 amperes. It will be seen that the maximum height of the curve is 230 volts from the mid-point, so that from brush to brush we have 460 volts. The field distortion has brought about a diminution of voltage of 8 per cent.

The chain-dotted curve DD' in Fig. 236 gives the voltage distribution on the commutator when the machine is running at full load with excitation increased to 7650 ampere-turns per pole. The total height of this curve is 518 volts.

It will be seen in Fig. 233 that two vertical lines N_1N_1 and N_2N_2 have been drawn. The line N_2N_2 represents the projection of the positive magnetic neutral plane (see page 279); that is to say, the plane that is being cut by the positive conductors and in which no E.M.F. is being generated. The line N_1N_1 is the projection of the negative magnetic neutral plane. The shape of the potential curve depends upon the distribution of magnetization. At no-load it will in general be a symmetrical curve, and the lines N_1N_1 and N_2N_2 will lie on the planes midway between the poles, which are sometimes spoken of as the mechanical neutral planes. If, however, there is any distortion of the field due to armature reaction, the potential curve will be distorted, as shown by curve B in Fig. 236, and the magnetic neutral planes will not lie on the mechanical neutral planes.

Assuming that the shape of the potential curve is definitely ascertained, the voltage between the positive and negative brushes will depend upon the bars in contact with the brushes. If, for instance, in Fig. 236 the brushes are on the magnetic neutral plane, the voltage will be the highest that can be obtained from the generator with the given state of magnetization. If, however, the brushes are rocked either forward or backward, assuming that the magnetization remains as before, the voltage between them will be smaller. For instance, the brushes may be rocked forward through the distance a and a'; the voltage between them will now be given by the difference of potential between a and a'. Or the brushes may be rocked backward through β and β'; the voltage between them will now be given by the difference of potential between b and b'. This is an effect independent of any change in the magnetization of the machine. This lowering of the pressure due to rocking of the brushes to points on the commutator at which the potential difference is lower may for convenience be spoken of as "depotensing," to distinguish it from the "demagnetizing" effect also brought about by the rocking of the brushes. The latter effect is considered in the next paragraph.

If we have a ring winding as shown in Fig. 12, and draw current out of it at any point A, we produce a pole at that point. The same effect occurs on a drum winding. If the brushes of a D.C. generator are so placed as to take current out at the positive and put current

in at the negative conductors that are exactly midway between the field poles, then the only weakening of the field that will occur from the armature reaction will be that arising from the saturation of the iron, as considered under heading (*b*). If, however, the brushes are rocked forward so as to collect and put down current in an unsymmetrical position, the armature magnetomotive force will have a component that directly opposes the field magnetomotive force. Thus if the brushes are rocked forward by an angle ϕ on a two-pole machine, the total demagnetizing armature ampere-turns *per pole* are given by the expression $\frac{\phi}{2\pi}\times$total conductors$\times$amperes per conductor. On a multipolar machine the demagnetizing armature ampere-turns per pole are equal to $\frac{\phi p}{\pi}\times$conductors per pole$\times$amperes per conductor, where ϕ is the mechanical angle rocked through and p is the number of pairs of poles. If on a generator the brushes are rocked backwards by an angle β, then there is a component of the armature ampere-turns that tends to strengthen the poles, and this will go to neutralize the depotensing effect mentioned above. In considering the rocking of the brushes, we must remember that the total effect is the algebraical sum of the demagnetizing and the depotensing effects.

If we start with a shunt generator at no-load with the brushes on the mechanical neutral, and put load on it without rocking the brushes forward, the armature distortion will carry forward the magnetic neutral plane, and the brushes will therefore no longer be at the highest and lowest points of the potential curve. They will, in fact, be at cc' in Fig. 236. Thus, in addition to the lowering of the voltage due to the reduction in the field form by saturation under heading (*b*), we have the lowering of the voltage due to the fact that the brushes are no longer on the highest and lowest points of the potential curve. If now we rock the brushes forward so as to bring them on to the highest and lowest points of the B curve, we immediately cause the armature to have a demagnetizing component; and the reduction of voltage due to this effect will, in general, be greater than the advantage gained by doing away with the depotensing effect.

Curves AA', BB' and DD' give the voltage distribution on the commutator of a machine not provided with commutating poles. If commutating poles are added and excited in such a way as to give the alteration in the field form shown by the dotted curve at C_1 and C_2, Fig. 233, the potential distribution on the commutator will be altered. Curve EE' (Fig. 236) shows the distribution of potential.*

* No correction has been made in the curve EE' for the effect of self induction of the winding. This is given in Fig. 241.

on the commutator on the machine provided with commutating poles when running at full load. This curve is the integral of the chain-dotted curve DD' in Fig. 233, with the added areas of field form shown at C_1 and C_2. As the curve EE' is the integral of the field form, the slope of EE' is everywhere proportional to the ordinates of the field form. In particular, the slope of the curve at E_c is proportional to the ordinate C_2. The slope of the curve at this point is proportional to the commutating voltage. We shall have something more to say about this in Chapter X.

When the brushes are rocked forward or backward, the variation of the voltage may be attributed to four distinct phenomena:

(1) The voltage varies because the movement of the brush brings us to a new point on the potential distribution curve.
(2) The voltage varies because ampere-turns are subtracted from or added to the field ampere-turns.
(3) When the machine is provided with commutating poles, the commutator flux decreases or increases the E.M.F. according as the brushes are rocked forward or backward.
(4) The value of the shunt excitation is changed by an amount dependent upon the sum of all the effects in 1, 2 and 3, and this fact increases the effect of this sum.

In any given machine it is possible to estimate approximately the effect of 1, 2, 3 and 4 in varying the voltage for any given brush position. As an illustration, we have worked out each of the effects so far as they are operative on the 1000 K.W. machine mentioned. The values obtained give us an idea of the order of each of the effects as found in a normal D.C. generator.

The first step is to lay out the top part of the potential distribution curve on a much larger scale than shown in Fig. 236. On an actual machine the voltage distribution on the commutator can be measured as described on page 282, or if we are given the exact field form in the vicinity of the neutral line we can lay out the potential distribution curve as indicated on page 252.

It should, however, be noted here that where a number of coils are grouped together in one slot (as is commonly the case with 500 volt D.C. generators), the potential on the commutator at any fixed distance from the neutral is not a constant, but varies over a considerable range as the slots take up various positions in the magnetic field. In order to determine the limits between which the voltage varies at any point, we may proceed as follows:

Fix upon a convenient number of points for drawing the ordinates of the potential distribution curve of the machine in question. On the machine under consideration there are 48 bars. It is convenient to fix upon ordinates which are one commutator bar apart,

that is to say, one-forty-eighth of a pole pitch apart. The pitch of the commutator bars is 0·2 inch; we have therefore taken five ordinates to the inch along the face of the commutator. We consider the case of the machine without commutating poles. Taking the value of the ordinates of the field form and converting these to average voltage generated during the passage of a conductor from one ordinate to the next, we arrive at the following figures:

0, 0·08, 0·25, 0·5, 0·82, 1·3, 2·1, 4, 7·8, 10, 11·5, 12·5, 13·4, 14·3.

In the machine in question there are four conductors side by side in one slot; and as the voltage in these four conductors will be practically the same at any instant we can lay out the voltage between bars for various positions of the armature, as shown in the accompanying Table III. The machine in question has a full-pitch winding, so that each of the two conductors forming a coil is in phase with the other, and the figures 0·08, 0·25, etc., give the mean voltage generated between bars as the bars move from one position to the next.

TABLE III.—VOLTAGES BETWEEN BARS OF COMMUTATOR IN VARIOUS POSITIONS.
Four Commutator Bars per slot. Full-pitch Winding.

No. of Ordinate	−3	−2	−1	NEUTRAL	1	2	3	4	5	6	7	8	9	10	11	
No. of Bar	−3	−2	−1		1	2	3	4	5	6	7	8	9	10	11	12
1st Position	−0·82	0	0		0	0	0·82	0·82	0·82	0·82	7·8	7·8	7·8	7·8	13·4	16·4
2nd Position	−0·5	−0·5	+0·8		0·08	0·08	0·08	1·3	1·3	1·3	1·3	10	10	10	10	14·3
3rd Position	−0·25	−0·25	−0·25		0·25	0·25	0·25	0·25	2·1	2·1	2·1	2·1	11·5	11·5	11·5	11·5
4th Position	−0·08	−0·08	−0·08		−0·08	0·5	0·5	0·5	0·5	4	4	4	4	12·5	12·5	12·5
5th Position	−0·82	0	0		0	0	0·82	0·82	0·82	0·82	7·8	7·8	7·8	7·8	13·4	13·4
6th Position	+0·5	−0·5	+0·08		0·08	0·08	0·08	1·3	1·3	1·3	1·3	10	10	10	10	14·3
7th Position	−0·25	−0·25	−0·25		0·25	0·25	0·25	0·25	2·1	2·1	2·1	2·1	11·5	11·5	11·5	11·5
8th Position	−0·08	−0·08	−0·08		−0·08	0·5	0·5	0·5	0·5	4	4	4	4	12·5	12·5	12·5

In the first position the centre of the slot is supposed to be on a neutral line, so that the E.M.F. in all four conductors is zero. The centre of the second slot is four ordinates away from the neutral line, so that the mean E.M.F. generated in each of the four coils is 0·82 volt, and so on. In the second position, the armature has moved through one-forty-eighth of the pole pitch, so that the E.M.F. in all four coils in the slot nearest the neutral is 0·08; in the second slot the mean E.M.F. in the coils is 1·3 volts, and so on for various positions, as indicated in Table III. If we now make a summation

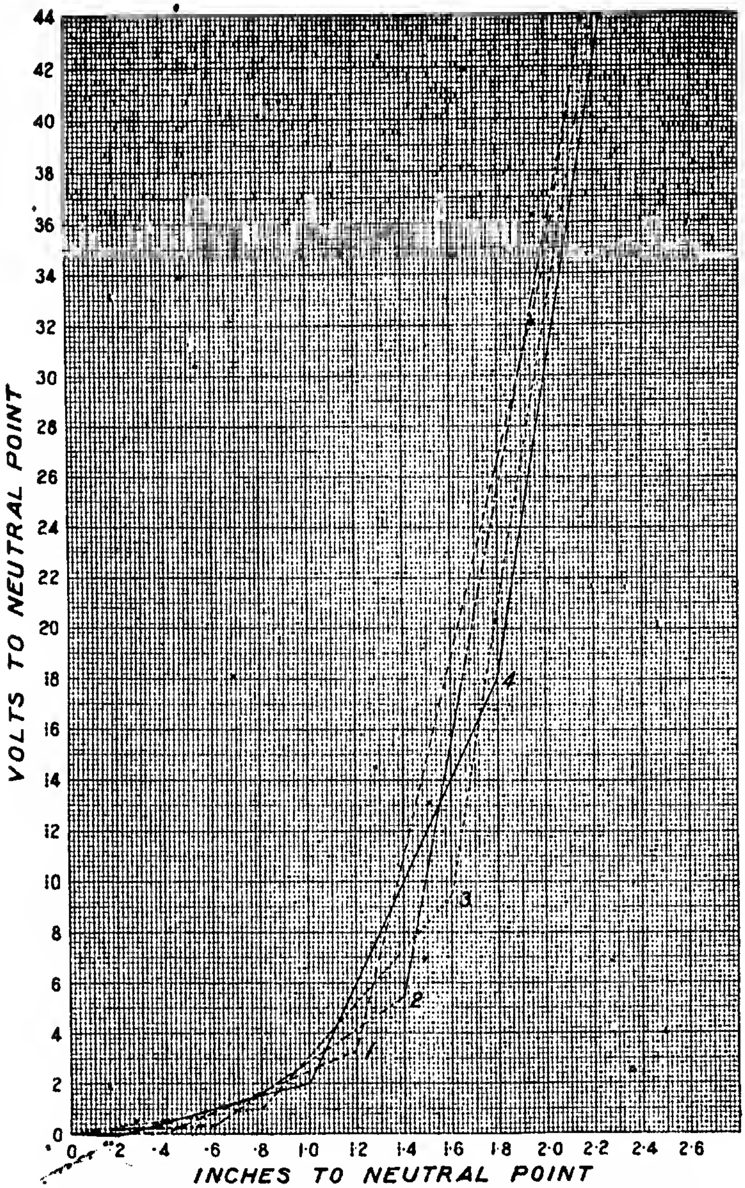


FIG. 238.—Showing how the voltage at any given position on the commutator pulsates owing to the grouping of the conductors in slots. Full pitch winding.

of all the voltages between bars in the first position, we obtain the dotted curve shown at 1 in Fig. 238. A summation of all voltages between bars in the second position gives curve 2. The third position is shown by curve 3; and so on. Thus we see that, for a commutator bar 1·2 inches away from the neutral, the potential

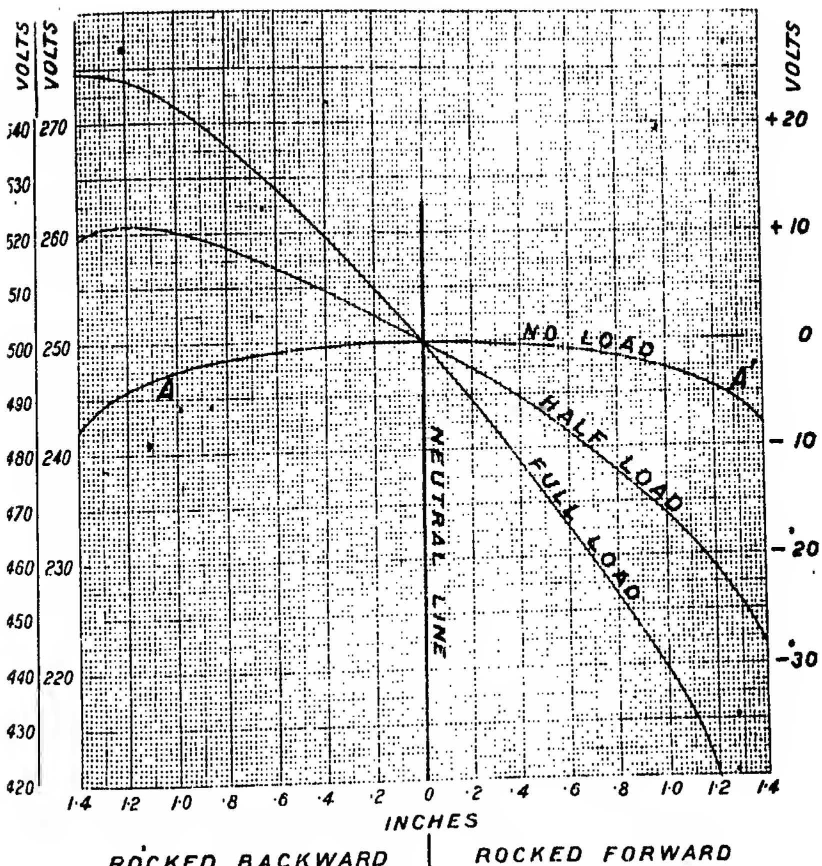


FIG. 239.—Curves of voltage distribution on a commutator near the no-load neutral line.

varies from 3·3 to 6 volts; and for a bar 1·4 inches away from the neutral the voltage varies from 5·4 to 11 volts. The variation of the voltage in the vicinity of the neutral is much smaller. At 0·4 inch away the potential varies from zero to 0·6 volt. This variation has a marked effect upon the commutation, and is referred to again in Chapter X., p. 341. We call attention to it here only because it is

necessary to point out that in drawing a potential distribution curve for the purpose of arriving at the effect of rocking the brushes one can only draw a *mean* potential curve. In Fig. 239, curve AA' gives the voltage distribution on the commutator in the vicinity of the neutral line drawn to a larger scale than in Fig. 236. This curve is arrived at by taking the mean values from Fig. 238. It will be seen that the ordinates are given to two different scales. On the left-hand side of the figure one scale gives the potential of the bar above a bar on the commutator half-way between brushes, that bar being arbitrarily taken at zero potential. This scale is convenient, because in going from bar to bar on the figure we see at once the voltage between bars. The figures on the other left-hand scale are just double of those in the first-mentioned scale, and give the voltage between brushes when the brushes are rocked to various positions. It will, of course, be understood that while we are rocking a brush forward and bringing down the potential of one brush we are at the same time varying the potential of another brush, so that the effect is doubled; and it is convenient to read off the double effect from one figure. If there were no magnetizing or demagnetizing effect, the variation of voltage as we rock the brushes forward or backward would be that given by curve AA'.

Magnetizing ampere-turns of the armature. As is well known, the armature exerts no magnetizing or demagnetizing effect if the current is led in and taken out exactly on the mechanical neutral line. On this machine, if the current is collected at a point one commutator bar forward of the neutral line, there will be 666·6 ampere-turns per pair of poles demagnetizing effect, or 333·3 ampere-turns per pole at full load.

Referring now to the full-load curve C in Fig. 234, we can find the change in voltage brought about by these demagnetizing ampere-turns. There are 496 turns in the shunt coil, so that 15 amperes gives an excitation of 7450 ampere-turns per pole at no-load with 33·3 ohms in the shunt circuit when running at full load in the vicinity of 500 volts. Now, 333·3 divided by 496 is equivalent to 0·672 ampere in the shunt coil. From curve C, Fig. 234, we see that a change of excitation of 0·672 ampere gives a variation of 10·5 volts, so that if the brushes are rocked forward by an amount of 0·2 inch measured on the commutator (one bar pitch) the voltage will fall by an amount equal to 10·5 volts, in addition to the small amount due to the variation of the position on the potential curve. If the brushes are rocked forward by four bar pitches to a point 0·8 inch ahead of the neutral, the number of demagnetizing ampere-turns will be 1322, equivalent to 2·67 amperes in the shunt. Curve C, Fig. 234, shows that this gives rise to a drop of 44 volts, so that when the brushes are rocked forward by this amount we have a total

drop of 47 volts, made up of 3 volts due to a change of position on the potential curve and 44 volts demagnetizing effect.

When the brushes are rocked backward, the armature ampere-turns give a magnetizing effect, the amount of which can be worked out in the same manner and plotted as in Fig. 239. But in this case the drop in potential due to the change of position on the potential curve must be subtracted from the rise in voltage due to the magnetization produced by the armature. Fig. 239 gives the change in voltage with change of brush position at half-load and full-load on the generator, particulars of which are given on page 250, the armature winding having a full pitch.

Effect of short-chording of armature winding. It is the common practice to make the throw of an armature coil one slot short of full pitch. The result of this is to wipe out the magnetizing effect of the current carried in one slot per pole, because the current carried by the upper coil is in the direction opposite to the current carried by the lower coil. The neutralization of the ampere-turns in this slot does not, however, influence the amount of magnetizing effect obtained when the brushes are rocked forward or backward. The rocking of the brushes forward by one slot will still give to the current carried in two slots its full demagnetizing effect per pair of poles. The effect of a short-chorded winding is to make the curve giving the potential distribution on the commutator a somewhat steeper slope near the neutral line. Moreover, where the armature is short-chorded by one complete slot, the variation of potential at some points on the commutator away from the neutral varies through wider limits. These facts will at once be apparent from an inspection of Table IV., and the various curves in Fig. 240; these are obtained

TABLE IV.—VOLTAGE BETWEEN BARS OF COMMUTATOR IN VARIOUS POSITIONS.
Four Commutator Bars per slot. Winding short-chorded by one slot.

No. of Ordinate	−3	−2	−1	NEUTRAL	1	2	3	4	5	6	7	8	9	10	11	
No. of Bar	−3	−2	−1		1	2	3	4	5	6	7	8	9	10	11	12
1st Position	−1·175	0	0		0	0	1·175	1·175	1·175	1·175	6·8	6·8	6·8	6·8	12·9	12·9
2nd Position	−0·69	−0·69	+0·21		0·21	0·21	0·21	2·25	2·25	2·25	2·25	8·25	8·25	8·25	8·25	13·65
3rd Position	−0·41	−0·41	−0·41		0·41	0·41	0·41	0·41	4·3	4·3	4·3	4·3	10·1	10·1	10·1	10·1
4th Position	−0·21	−0·21	−0·21		0·21	0·69	0·69	0·69	0·69	5·6	5·6	5·6	5·6	12·1	12·1	12·1
5th Position	−1·175	0	0		0	0	1·175	1·175	1·175	1·175	6·8	6·8	6·8	6·8	12·9	12·9
6th Position	−0·69	−0·69	−0·21		0·21	0·21	0·21	2·25	2·25	2·25	2·25	8·25	8·25	8·25	8·25	13·68
7th Position	−0·41	−0·41	−0·41		0·41	0·41	0·41	0·41	4·3	4·3	4·3	4·3	10·1	10·1	10·1	10·1
8th Position	−0·21	−0·21	−0·21		0·21	0·69	0·69	0·69	0·69	5·6	5·6	5·6	5·6	12·1	12·1	12·1

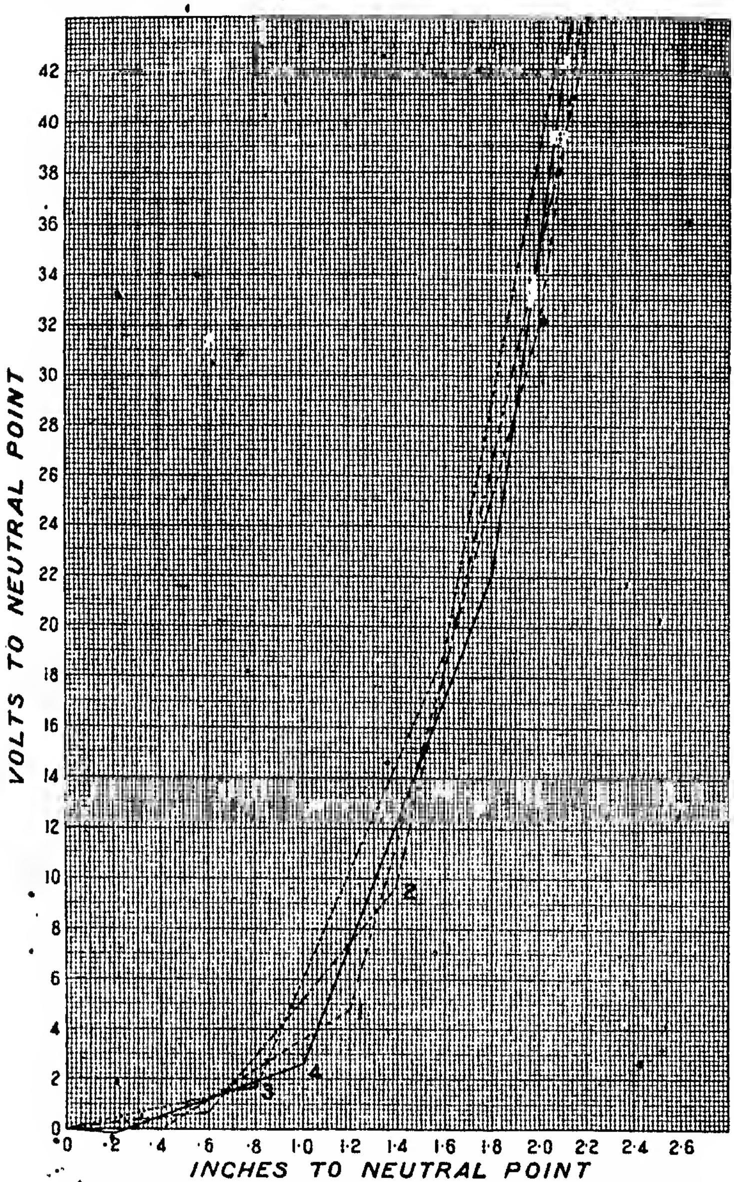


FIG. 240.—Showing how the voltage at any given position on the commutator pulsates owing to the grouping of the conductors in slots. Winding short-chorded one slot.

by taking the sums of the individual voltages between bars with the commutator in various positions.

In Chapter X. these potential distribution curves are referred to again, and it is shown that for "half-stepped" windings the variation of voltage for any fixed point is much reduced.

For any given brush position we are able to draw curves like those marked c and c' in Fig. 235. Curve c shows the rise in voltage when the load is increased with the brushes rocked back one commutator bar. Curve c' shows the extra rise in voltage produced by the increase of the shunt current. Similarly, c'' gives the drop in voltage as the load is increased on the machine in question with the brushes rocked forward one commutator bar; c''' shows the extra drop produced by the shunt excitation.

(d) Effect of commutating pole. In order to study more exactly the effect on the voltage of rocking the brushes when the machine is provided with commutating poles, we must plot to a larger scale the potential distribution curve in the neighbourhood of the neutral.

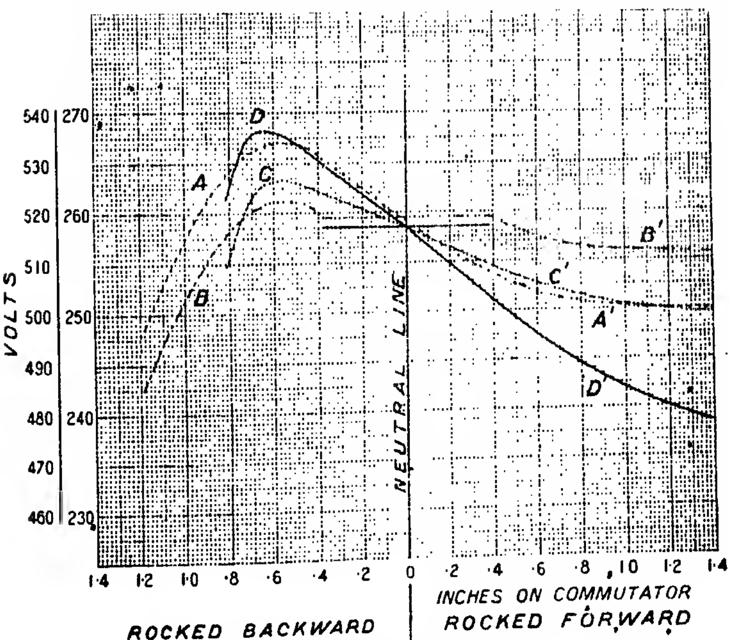


FIG. 241.—Showing effect of rocking the brushes in a generator provided with commutating poles. See p. 326.

This has been done for the machine in question in Fig. 241, where the dotted curve AA' shows the distribution of potential in the

vicinity of E_c, Fig. 236, plotted to a larger scale. The reason why the potential is at 259 and not at 250 on the neutral line is that the excitation of the shunt winding has been increased to allow for various drops, which we have considered in the foregoing. If the commutating pole is symmetrically placed upon the neutral line and the brushes are also on the neutral, no increase of voltage will result from the normal excitation of the commutating pole. It should be explained that the curve *AA′* gives the hypothetical potential distribution on the commutator, on the assumption that full-load current is passing in the armature and around the commutating pole, but that there is no disturbance of the potential due to the self-induction of the armature winding operating (as it does in fact operate) to oppose the voltage generated by the commutating pole.

We have, in fact, a brush of a certain width (in this case 0·76 inch) resting upon the commutator and collecting current from the commutator bars. As the current is collected from the bars, its value in the coils under commutation changes, and a back E.M.F. of self-induction is set up, which opposes the voltage generated by the commutating pole and (in the ideal case) just exactly neutralizes that E.M.F., so that the potentials of all the bars under the brush assume a constant value, which will be very near the mean value of the potentials of the bars given by the curve *AA′*. The curve *BB′* shows the distribution of potential brought about by the circumstances described above. The ordinates of the flat part of the curve have the mean value of the corresponding ordinates of the *AA′* curve. The shape of the curve beyond the region affected by the brush is as before, except that the curve to the left of the figure is pulled down by the self-induction of the coils under the positive brush, and the curve to the right is raised by the operation of self-induction in the coils under the negative brush. The effect of the self-induction is simply to neutralize the voltage generated by the commutating pole, so that there is no voltage between the bars under the brush. It will be seen that a black line has been drawn below the flat part of the curve *BB′* one volt lower down; this black line gives approximately the potential of the brush, which is about one volt lower than the potential of the bars under the brush. The curve *BB′* in Fig. 241 has been drawn on the assumption that the brushes are on the neutral line. By the same construction it is possible to find the potential of the brush when rocked slightly forward or slightly backward. This is given by the curve *CC′*.

We see then that when the brushes are rocked backward from the neutral line the strengthening of the commutating pole with increase of load causes a rise of voltage. This effect is in addition to the effect considered under heading (*c*). The two effects together may on some generators be more than sufficient to compensate for

effects considered under headings (*a*) and (*b*), which would otherwise tend to bring down the voltage on load. A machine may be over-compounded by making use of the (*c*) and (*d*) effects. Where this is intended, it should be designed so that the saturation effect considered under (*b*) is not too great; and the commutating pole should have a fairly wide face, so as to allow the (*d*) effect to be increased by having the brushes well rocked back.

For any given position of the brushes it is easy, from values taken from curve CC' in Fig. 241, to plot a curve such as d in Fig. 235, which gives the rise in voltage with increase of load due to the (*d*) effect on the 1000 K.W. generator under consideration when the brushes are rocked back 0·4 inch behind the neutral point. Any rise of voltage, d, if it were not swamped by drops in voltage due to (*a*) and (*b*), would be accompanied by an additional rise due to the increase in the shunt current. The curve d' gives the sum of the (*d*) effect and the increase in the shunt excitation accompanying it. If the brushes were rocked forward to a point 0·4 inch in front of the neutral point, the commutating-pole flux would cause a fall in voltage, as shown by the curve d'', and with the change in the shunt current there would be a further drop, shown by the curve d'''.

The curves a, b, c and d in Fig. 235 have been plotted to show the approximate amount of change of voltage that may be expected from the various causes set out above on a modern D.C. generator. For any particular load and for any given position of the brushes, the total change in voltage to be expected can be ascertained by taking the algebraic sum of each of the effects (*a*), (*b*), (*c*) and (*d*), and then making an allowance for the change in the value of the shunt current by reference to Fig. 234.

(e) **Magnetizing or demagnetizing effect of short circuit current under brushes.** There is yet another influence which may operate to raise or lower the voltage on load. It not infrequently happens that the commutation of the current, in the coils short-circuited by the brushes, takes place in a manner very different from the ideal manner that we assumed when constructing Fig. 241. If the commutating pole is too weak, the commutation may be delayed until the very last instant before the bars break contact with the brushes. The greater part of the current is then collected by the toe of the brush, and the effect is somewhat the same as if the brushes had been rocked further forward. If the commutating pole winding is so weak that it permits the armature to produce a field of wrong polarity under the pole, there may be an eddy current under the brushes so great that the current in the heel of the brush is flowing in the wrong direction and the current density under the toe of the brush may be exceedingly high. This eddy current in an armature has the effect of weakening the main poles in the same manner as

the current in the armature coils when the brushes are rocked forward. It may lead to a very serious drop in voltage as the load comes on. If, on the other hand, the commutating pole is too strong, the current in the short-circuited coils reverses too quickly and the current density at the heel of the brush becomes excessive, being fed by a reversed current at the toe of the brush. The current in the short-circuited coils has then a magnetizing effect, and may yield a very decided compounding effect when the brushes are wide and the commutating pole is much stronger than is required for correct commutation. In cases where the commutating pole is saturated at full load and unsaturated at half load, it may be that the commutating pole is too strong at light loads and too weak at heavy loads, so that as the load is increased from zero we have first a compounding effect due to the commutating pole and then a decompounding effect. This is one of the causes of the marked curvature found in the load-voltage characteristics of some D.C. generators. The effect described in this paragraph is not amenable to calculation, because so much depends upon the resistance of the brush contact at various points along its surface, and this again depends upon the way in which the brushes are bedded and upon the way in which the surfaces are worn or burnt away.

DEFECTS IN REGULATION.

I. SHUNT-WOUND GENERATORS.

A guarantee as to the regulation of a shunt generator, when given independently of the engine, generally specifies the percentage drop in the voltage between no-load and full load when the machine is run at constant speed. In ordinary commercial machines no attempt is made to make the drop in voltage particularly small. The greater the drop in voltage, the greater the ease with which the load is distributed between the different generators. From 8 to 12 per cent. drop is generally regarded as sufficiently satisfactory; and many machines having a high ratio of armature ampere-turns to field ampere-turns and considerable saturation in the armature teeth will give a drop in voltage from 15 to 20 per cent. at füll load.

When a machine fails to meet the guarantee, the cause or causes of the defect will be found to be one or more of the effects (*a*), (*b*), (*c*), (*d*) or (*e*) set out on pages 248 to 267 above. There is not much difficulty in finding out which of the causes is operative.

The first step is to rock the brushes to the neutral point. (See page 279 as to methods of finding the neutral.) All the brush-holders should be inspected, to see that the spacing of the arms is reasonably good (see page 331 as to methods of checking the spacing).

The commutating pole should then be adjusted until the voltage drop under the brushes assumes a reasonably good characteristic (see page 336 as to methods of taking the brush drop). In this way we eliminate effects (*c*), (*d*) and (*e*), or reduce them to a very small amount.

By measuring the resistance of the armature circuit, including the commutating-pole winding and connectors to the switchboard, we are able to calculate the effect (*a*). After eliminating (*c*), (*d*), and (*e*) and allowing for (*a*), we arrive at the effect (*b*), which is not uncommonly of considerable magnitude.

The machine is run at a constant speed (or, if this is impossible, the speed is measured accurately, and allowance is made for change in speed). The voltage is measured at different loads, and the constant-speed voltage characteristic is plotted from no-load to overload. Next the (*a*) effect is calculated, and the (*b*) effect is plotted on a separate sheet. The (*b*) characteristic invariably shows a good deal of curvature (see *b*, Fig. 235). On commutating-pole machines the curvature is sometimes increased by the effect described on page 266. It is the curvature of the characteristic that causes the chief difficulty in making D.C. machines share the load when they are connected in parallel (see page 372).

Method of reducing the drop in voltage due to the saturation of the teeth. After a machine has been designed and built, it is too late to think about reducing the saturation of the teeth at no-load; but a great deal can often be done to reduce the super-saturation that occurs at full load in the teeth under the trailing horn of the pole (see Fig. 233).

The simplest plan, if it can be carried out without calling for too great an exciting current, is to lengthen the air-gap. This can sometimes be done by merely taking out liners from under the poles where liners have been provided. Where liners have not been provided, the air-gap may be increased by boring it out. This, however, must not be done until it has been ascertained whether it is permissible to lengthen the air-gap by an appreciable amount without running into other troubles. The three troubles to be feared from the lengthening of the air-gap are:

(1) Heating of field coils owing to greater exciting current.
(2) Inability to obtain the required exciting current owing to the resistance of the field coils.
(3) Failure to meet efficiency guarantees.

A heating test will show whether there is a substantial margin in the cooling conditions, which will enable the current to be substantially increased without exceeding the guaranteed temperature rise. In cases where a good margin has been provided in the rheostat,

it will be possible to get sufficient exciting current without rewinding the shunt coils. In considering the effect on the efficiency, it must be remembered that an increase of the air-gap on a D.C. machine is often accompanied by a reduction in the pole-face losses; and this may go a long way to compensate for the increased losses in the shunt coils. If it is found that the field current can be increased substantially without fear of any of these troubles, the next step is to make a rough calculation to ascertain by what amount the saturation of the teeth will be reduced by increasing the air-gap by the amount which is seen to be permissible. This is best done by laying out * an air-gap-and-tooth-saturation curve, and from it the field form at full load. This should be done for both cases: (1) with the air-gap as it is, and (2) with the air-gap as proposed. It will then be seen whether any substantial improvement can be effected by the simple means of lengthening the gap. It will generally be found that unless the gap can be very substantially increased the improvement in the full-load conditions is not very marked.

A very much more effectual way is to taper the air-gap so as to make it great under the trailing horn and small under the leading horn of the pole. We are here speaking of a generator; for a motor the taper should be reversed. The effect is to make at no-load an unsymmetrical field, which becomes more symmetrical as the load comes on, so that at full load the saturation under the trailing horn is not at all excessive.

Fig. 242 shows the way in which the 1000 K.W. generator described on page 250 would be improved by giving a taper to the gap. Under

FIG. 242.—Showing way of tapering the air-gap of a generator to minimize field distortion.

the leading horn of the pole the gap is only 0·2 cm.; while under the trailing horn it is 1 cm. If we wish to calculate roughly the effect of so tapering the gap, the first step is to plot a number of air-gap-and-tooth-saturation curves, as shown in Fig. 243. In this figure the saturation curves are plotted for gaps 0·2, 0·4, 0·6, 0·8 and 1 cm. respectively. The abscissae show the number of ampere-turns expended on the air-gap and the teeth of the armature for different flux-densities in the air-gap. If now we make a plot of

* See *Specification and Design of Dynamo-Electric Machinery*, p. 78.

the distribution of M.M.F. along the air-gap for any particular load, as was done in Fig. 233, we can by means of Fig. 243 plot the field form for that particular load.

Curve A in Fig. 244 shows the same field form as in Fig. 233 for the 1000 K.W. generator running at no-load with a symmetrical air-gap. Curve B shows the no-load field form with the taper gap. The excitation is taken at 6000 ampere-turns per pole. Curve C

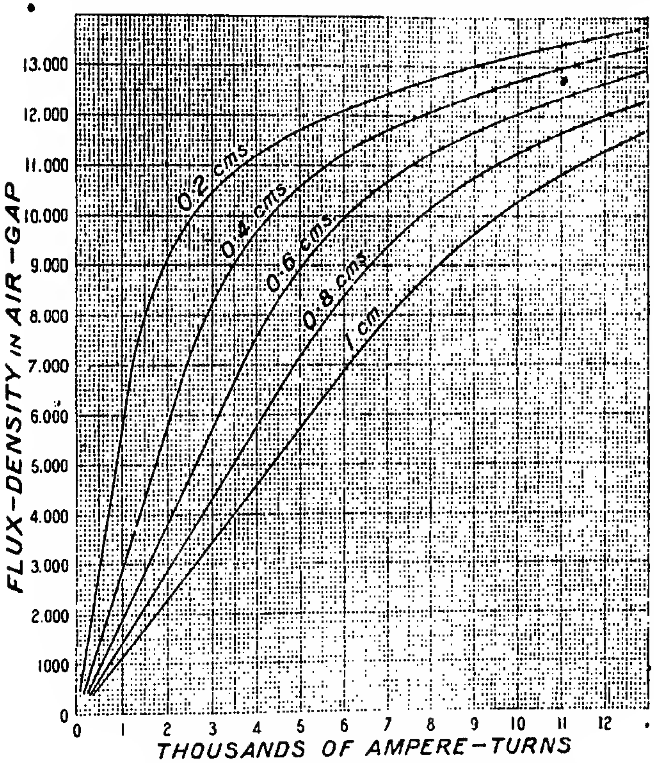


FIG. 243.—Air-gap-and-tooth-saturation curves for various lengths of gap.

shows the field form at $\frac{1}{2}$ load, and curve D the form at $\frac{3}{4}$ load. The full-load curve is marked E; it will be seen that it is more nearly symmetrical than B in Fig. 233, which is drawn for the same excitation (6000 ampere-turns) and the same load. It will be seen that in curve B, Fig. 233, the flux-density runs up to 12,200 at the highest point, whereas in curve E, Fig. 244, the highest flux-density is 11,100.

Taking the area of curve A to represent 500 volts, we can find

the voltage generated at any load by multiplying the area of the curve for that load by the constant

$$\frac{500}{\text{Area of } A}$$

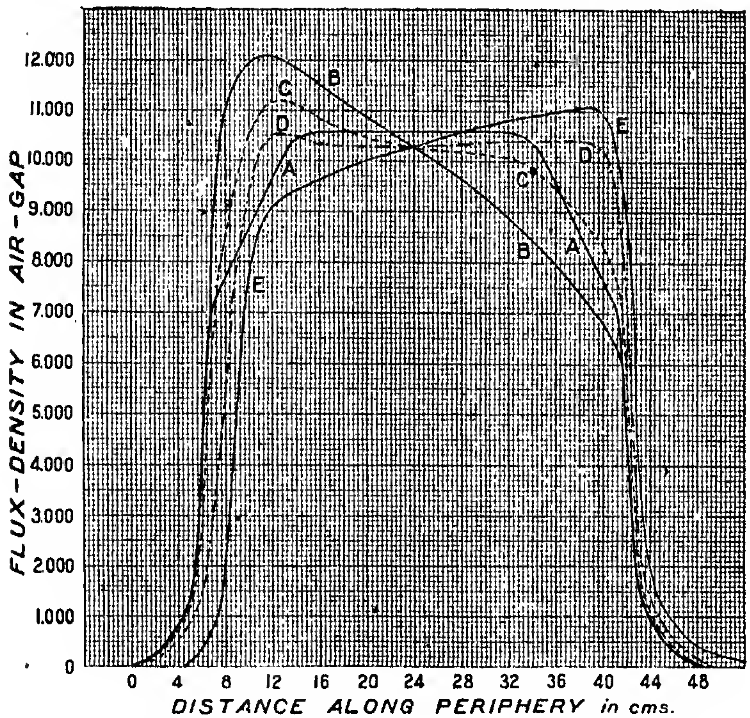


FIG. 244.—Showing amount of field distortion on generator with tapered air-gaps, at various loads.

It will be found that as the load is increased from zero, the areas increase. This is because of the high saturation under the leading horn of the pole, which for small changes of load does not permit of as much change of the flux under that pole as occurs under the trailing horn when the flux is increasing. After three-quarter load is reached, the saturation under the leading horn disappears, and the areas gradually diminish with increase of load.

If we plot the voltages generated at the different loads, we get a curve like that shown in Fig. 245. This curve has about the same curvature as curve *b* in Fig. 235. By still further increasing the air-gap under the trailing horn and increasing the ampere-turns on the

pole, the rise of voltage can be continued up to the full-load point, and the curve then becomes rather flatter.

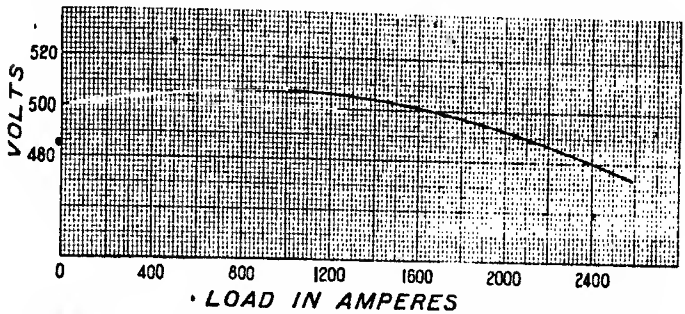


FIG. 245.—Showing improved regulation with tapered air-gap. Compare curve *b*, Fig. 235.

II. COMPOUND-WOUND GENERATORS.

When a field winding connected in series with the armature is added to the shunt winding for the purpose of counteracting the various drops in voltage that we have considered in the preceding, it is found that it cannot be made to neutralize exactly the effect of these drops, because the series ampere-turns are strictly proportional to the load, whereas some of the effects mentioned above (notably the effect (*b*), page 248), are not proportional to the load. Moreover, the magnetic circuit of the generator is usually more or less saturated, and this gives a further curvature to the characteristic of the compound-wound machine. If, for instance, we add a series winding of one turn per pole to the 1000 K.W. D.C. generator whose shunt characteristics are given in Fig. 235, it will be found that the load characteristic takes the form shown in curve *A* in Fig. 246. If we adjust the compound winding to neutralize exactly the effects (*a*), (*b*), (*c*), (*e*) and (*s*) at the full-load point, so as to obtain the same voltage at no-load as at full load, it will be found that at intermediate loads the series winding more than neutralizes the drops caused by these effects and gives a voltage higher than at no-load. The increase of load above the full-load point will result in a drop in voltage below the no-load voltage. Thus the term "level-compounded," applied to a generator that has been adjusted in this way, is somewhat misleading.

When the series winding is adjusted so as to give a considerable rise in voltage at full load, in order to compensate for the drop in the line, it will invariably be found that there is a considerable curvature in the characteristic, due to the causes mentioned above (see curve *B*, Fig. 246). For the same increments in the load

the voltage will rise more rapidly at a light load than at a heavy load.

Machines of different designs, and even machines of the same designs when differently adjusted, may have considerable differences in the amount of curvature of the load characteristic; and this may lead to difficulties in the distribution of load between machines running in parallel.

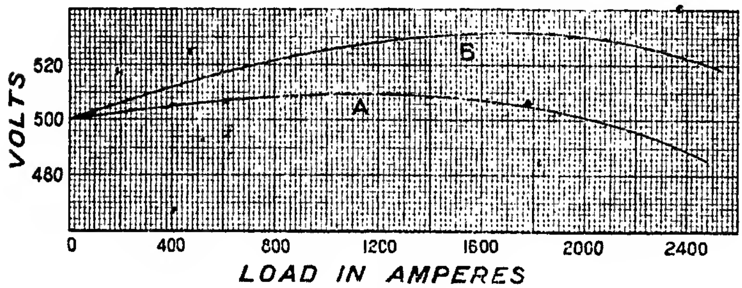


FIG. 246.

Equalizing of compound-wound D.C. generators.

When compound-wound D.C. generators are to be run in parallel, it is necessary to connect the series windings of the two generators to an equalizer bar, as shown in Fig. 247. The effect of this connection is to give a common supply of current to all the series windings. If this is not done, any one machine that for the moment is giving more current than its neighbour will have its voltage raised higher than that of its neighbour, and the load will go on increasing more and more until it brings out the circuit-breakers.

Effect of resistance in equalizer bar and connections.

If the resistance of the equalizer bar and the connections between it and the generators is too high, it will fail to do its duty, and the compound-wound generators will not run in parallel. This matter is most easily studied by taking the case of two exactly similar generators, A and B, connected in parallel as shown in Fig. 247. The resistance of the series winding in each machine is denoted by R and the resistance of the equalizer connection by r. In the first place, we shall assume that the characteristic of each machine when operating as a *shunt* generator (series winding cut out) is such that the voltage generated changes with the load according to the law

$$V = V_0 - k_1 I,$$

where I is the load current in the machine and k is the negative slope of the characteristic (taken for the moment as constant). When

the series winding is in operation we shall assume that its effec is strictly proportional to the current, S, flowing through it so tha

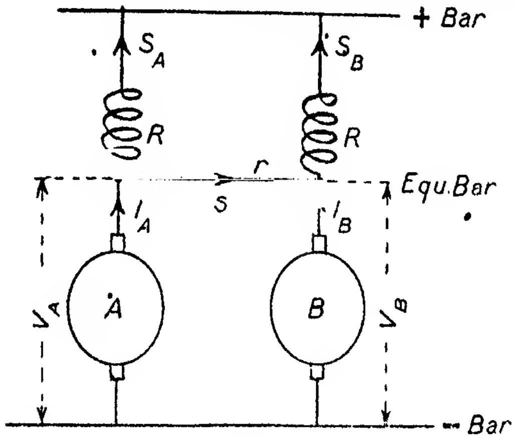


Fig. 247.

the voltage of the compound-wound generator changes with the load according to the law

$$V = V_0 - k_1 I + k_2 S,$$

where k_2 is the slope we would have on the characteristic if k_1 were zero and I were equal to S. Thus for the two machines we have the laws

$$V_A = V_0 - k_1 I_A + k_2 S_A$$

and

$$V_B = V_0 - k_1 I_B + k_2 S_B,$$

$$V_A - V_B = k_1(I_B - I_A) + k_2(S_A - S_B).$$

Let the current in the equalizer be denoted by s. Then

$$V_A - V_B = rs = k_1(I_B - I_A) + k_2(S_A - S_B).$$

From the diagram (Fig. 247) we have

$$I_A = S_A + s \quad \text{and} \quad I_B = S_B - s;$$

$$\therefore\ rs = k_1(I_B - I_A) + k_2(I_A - I_B) - 2k_2 s;\ (k_2 - k_1)(I_A - I_B) = rs + 2k_2 s.$$

Again, from Fig. 247, we see that

$$RS_A = rs + RS_B;$$

therefore $R(S_A - S_B) = rs$, so that

$$S_A - S_B = \frac{r}{R}s \quad \text{and} \quad I_A - I_B = \frac{r}{R}s + 2s.$$

Substituting in the equation above, we get

$$(k_2 - k_1)(r + 2R) = rR + 2k_2 R,$$

and finally

$$r = \frac{2Rk_1}{k_2 - (k_1 + R)}. \qquad \text{(1)}$$

Taking for the moment only positive values of r, this expression gives the limiting value of the resistance of the equalizer connections. For lower values the generators are stable, for higher values the generators are unstable. It will be seen that the limiting value is proportional to the resistance of the series windings and to the downward slope of the shunt characteristic. Where k_2 is greater than (k_1+R) the machine acts as an over-compounded generator. Where k_2 is much greater than (k_1+R) the limiting value of r is small. Where k_2 is only slightly greater than (k_1+R) the machine acts more nearly as a level-compounded generator, and in this case the value of the equalizer resistance may be fairly great without endangering the stability. Where (k_1+R) is greater than k_2 the machine acts as an under-compounded generator; the limiting value of r is then negative, and the machine is stable for all positive values of r.

Instability of compound-wound generators.

It sometimes happens (especially in the case of turbo machines fitted with compensated windings) that compound-wound generators will not run well in parallel although the equalizer connections have been made with quite heavy cable. It may be that the generators are rather far from the switchboard where the equalizer bar is and the cable connections are rather long. There are two reasons why the conditions may lead to instability in the case of turbo-generators. In the first place, the resistance of the series winding, R, is usually very low in turbo-generators, and in the second place the value of k_1 is probably low because the resistance of the armature is very small; the effect (*b*) (page 248) is negligible when a compensating winding is employed, and the effects (*c*), (*d*) and (*e*) may easily be such as to reduce the value of k_1 or even to make it negative. In cases of this kind it may be costly and difficult to make any reduction in the resistance of the equalizer cables. The trouble may be cured by rocking the brushes forward so as to increase the value of k_1, or by putting resistance in series with the series windings so as to increase R. When the over-compounding is excessive some of the current may be diverted from the series windings. The effect of any changes can be approximately calculated from the formula (1) on page 275.

Equalizer on the same side of generator as the ammeter and single-pole breaker. Mr. E. P. Hill has drawn attention * to the large number of troubles that arise through want of knowledge of the function and proper position of equalizing connections. In cases where the switchboard is supplied by one firm and the generator by another the only person responsible for the co-ordinating of the

* *Electrical Engineer*, vol. x., page 462 (1914).

connections is the customer's engineer and he does not always realize the importance of certain details.

It is very important that the equalizer shall not be connected to the same side of the generators as the ammeters as shown in Fig. 248. If this is done it will equalize the current between the two ammeters and the switchboard attendant will not know when one machine is taking more load than the other. The mistake is very obvious when seen in a diagram as in Fig. 248, but on a switchboard where the connections are not so apparent the mistake may pass unnoticed and the trouble on the generators may be attributed to other causes. It is equally wrong to connect the equalizer on the same side as the single-pole circuit breaker as shown in Fig. 248, because it prevents

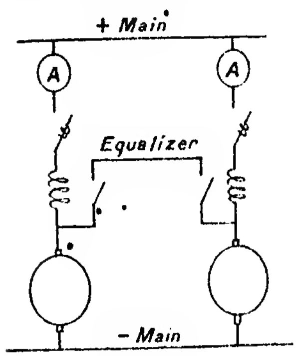


Fig. 248.

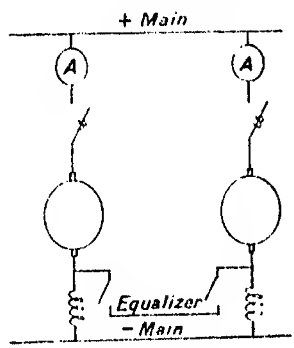


Fig. 249.

the circuit breaker from cutting out the machine on overload. If one of the generators is very much overloaded the current will divide between the two circuit breakers and neither will open until the load on one breaker reaches the overload value for which it is set. Before this occurs one of the generators may be taking more than twice that overload, because through some accident the other generator might be motoring. As soon as one breaker comes out it will throw double the load on the other, which will come out with a great bang. The right method of making the connections is shown in Fig. 249.

Should it be found that by an oversight one of these errors has been made, one way to overcome the trouble is to flash over the polarity of the generators and reverse the cables at the switchboard, thus putting the existing equalizer on the negative side (the single-pole breaker and the ammeter being usually on the positive side). If this is not practicable the ammeter must be changed over to the other side and an additional single-pole switch installed so as to get

a double break and ensure that each generator can be cut out independently when its load reaches a prescribed limit.

Instability of shunt-wound generators. When shunt generators are provided with commutating poles and an attempt is made to reduce the drop in voltage at full load by strongly exciting the commutating poles and rocking the brushes back, there is danger that at light loads the machines will be unstable between themselves, some acting as generators and others as motors. When an attempt is made to put load on one of the motoring machines by strengthening the field, it will suddenly take all the load, and other machines may then run as motors. This behaviour is more common with motor-generators run by synchronous motors at a perfectly constant speed than with engine-driven generators in which the drop in speed tends to equalize the load. The obvious cure is to see that the brushes are not rocked too far back, and that the commutating poles are not too strongly excited. Where the shunt characteristic is very much curved owing to the effect (*b*) (page 248), it may not be possible to make the drop in voltage at full load very small and at the same time preserve stability at light loads.

CHAPTER VIII

DIRECT-CURRENT GENERATORS (*Continued*)

Methods of finding the neutral point.

In the first place, it should be pointed out that some confusion arises owing to the different meanings attached to the expressions "neutral plane" and "neutral line." These terms are applied (1) in connection with the magnetic field of a generator; (2) in connection with the distribution of E.M.F. on a commutator.

(1) When used in connection with a magnetic field the neutral plane is an imaginary plane drawn midway between a north pole and a south pole parallel to the shaft, and may be defined as the plane in which there is no radial component of magnetic flux density. In a magnetic field distribution diagram, such as Fig. 233, the neutral plane is represented by the neutral line. When a machine is on no-load and has a field-form which is symmetrical about the centre line of each pole, the magnetic neutral plane is midway between the north and south pole. When the machine is loaded the magnetic neutral plane is moved in the direction of the rotation in the case of a generator and against the rotation in the case of a motor.

(2) In ordinary parlance the "neutral" means the neutral on the commutator. Here a distinction must be drawn between the "mechanical" neutral, the "no-load" neutral and the neutral at any particular load. When the field is perfectly symmetrical about the centre line of each pole the mechanical neutral and the no-load neutral are identical. The mechanical neutral plane on a commutator is an imaginary radial plane parallel to the shaft which cuts through the centre of a group of commutator bars which belong to a coil lying in two slots, when those slots are in such a position with respect to a pole that the flux is at its maximum and the E.M.F. in the coils is zero. In speaking of the bars which belong to a conductor of a certain coil, some confusion arises, because each coil is connected to two bars. To be perfectly precise, we should fix our attention upon the mica segments that lie between pairs of

bars,* each bar of the pair being connected to the coil in question. Thus for a coil consisting of four straps side by side there will be three mica segments across which the voltage generated in the four conductors is exerted. The centre of the three mica segments lies on the neutral plane when the coil in question embraces the maximum magnetic flux from any pole. In the case of a full-pitch winding the neutral on the commutator will lie on the centre of the group of mica segments, when the coil in question lies in the magnetic neutral planes. On a short-chorded winding a coil will lie between the magnetic neutral plane and the pole at the instant when the centre of its group of segments lies on the neutral of the commutator.

Sometimes by accident or design the distribution of the magnetic field is not symmetrical about the centre line of each pole. In this case the mechanical neutral differs from the no-load neutral. Where a machine is provided with commutating poles the residual magnetism of the commutating poles is generally sufficient to make a difference in the position of the mechanical and the no-load neutrals. The position of the neutral on the commutator will depend upon the arrangement of the end windings of the armature. Where the end windings are symmetrical so that the mica segment lying between the ends of a coil lies midway between the slots in which the coil lies, the mechanical neutral on the commutator lies opposite the centre line of the pole. It not uncommonly happens, however, that the end windings of the armature are not perfectly symmetrical so that the neutral point on the commutator lies a short distance before or a short distance behind the centre line of the pole. Very often the banding wires of the armature prevent one from tracing out the end windings of the armature and identifying a particular commutator bar as belonging to a particular conductor lying in a slot. Where no other means are available one can always identify a particular conductor as belonging to any particular bar by passing a current from the bar through to a needle point pressed through the insulation at the end of the machine opposite the commutator and working by the drop in potential method described on page 18. After the conductors lying in a particular pair of slots have been identified with the segments belonging to them and both marked with chalk in a conspicuous manner, the mechanical neutral can be found by turning round the armature until the two slots are near the magnetic neutral and stand in a perfectly symmetrical position with respect to the pole they embrace. The centre of the segments then lies on the mechanical neutral of the commutator.

* In the case of a series-wound machine, the mica segment to which we refer is the segment across which there is no voltage by reason of the fact that the sum of the E.M.F.'s in all the coils connecting the adjacent bars is equal to zero.

"Kick Neutral."

A favourite way of finding the no-load neutral is to connect the positive and negative brushes to the positive and negative terminals of a low reading voltmeter, and then to observe whether there is any deflection of the voltmeter when current is passed through the field circuit. By trying the brushes in various positions and noting the direction of the deflection produced, a position can be found at which no deflection is produced on the voltmeter when the field current is suddenly switched on or suddenly switched off. This point is commonly taken as the no-load neutral, and for practical purposes the method is often sufficiently accurate. It should be noted, however, that there are two sources of error which arise in this way of taking the no-load neutral:

(1) The slots may not be in a symmetrical position with regard to the poles.

(2) The point of contact of the brushes upon the commutator is rather indefinite, and it by no means follows that the average point of contact of all the brushes lies in the centre of the brush.

To get a more accurate indication of the position of the no-load neutral by the "kick" method, distinction should be drawn between lap windings and wave windings. In the case of a **lap winding** (on which the phase position of the slots with respect to the poles is usually the same for all poles) one can proceed as follows: Raise all the brushes except one positive brush and one negative brush. Turn the armature until a pair of slots carrying a coil near the neutral lies in a perfectly symmetrical position with regard to the pole that it embraces. Find the mica segments which separate the conductors of the single coils lying in the slots in question. If there are an even number of these, say four, there will be an odd number of bars included between the two outer mica segments. If there are an odd number of mica segments there will be an even number of bars embraced by the segments. Where there are an odd number of bars place a piece of copper wire between the centre bar and the positive brush, and another piece of copper wire between the centre bar and a negative brush. Connect the brushes to the voltmeter and turn on the field current. Move the armature a little one way or the other way until no deflection is obtained. The centre of the centre commutator bar is then upon the no-load neutral.

If there are an even number of bars, a piece of crinkled copper wire should be so placed that it connects both bars to a positive brush and another similar piece of wire should connect the two centre bars to the negative brush, and the same method employed as before. When no deflection is obtained on the voltmeter, the mica segment lying between the two centre bars lies on the no-load neutral.

On a series-wound armature the slots under one pole very commonly bear a different phase position from that of the slots under another pole. To get at the no-load neutral one must take the average effect of the conductors that connect two adjacent commutator bars. These form a wave winding distributed near the neutral points between each pair of poles all around the armature. This is best done by lifting up all the brushes except one on each brush-holder and grinding in that brush rather carefully so that it touches on the commutator fairly well in its middle region. The ordinary method of grinding in a brush with emery cloth leaves the face of the brush in such a shape that it tends to bear in the centre of the brush rather than at the edges. The positive and negative brushes are attached to the positive and negative terminals of a low-reading voltmeter. In the case of a series winding it is well to check the position of the neutral with the armature turned to various positions until the armature has been turned through 180 degrees. This is to avoid the effect of any dissymmetry that may exist in the air-gap.

Method of finding the neutral when the machine is running.

Sometimes it is inconvenient to shut down the machine to find the neutral by the "kick" method, and one must content oneself by exploring the face of the commutator with two voltmeter points held so that they are about the pitch of one commutator bar apart. A good place to do this exploring is on the radial end of the commutator, which should be previously polished with a little carborundum paper. It is better to use carbon points than metal points for this purpose. The two points are pressed upon the commutator, and while the distance between them is kept constant the pair of points is rocked backward and forward until a position is found at which no deflection is obtained upon a low-reading voltmeter.

Method of taking the voltage distribution curve on a commutator.

For many purposes it is desirable to know how the voltage is distributed around the commutator of a D.C. machine and to be able to plot a potential curve like that illustrated in Fig. 236. An apparatus suitable for the purpose is shown in Fig. 251. It consists of a guide-strip of fibre or leatheroid $\frac{1}{32}$" in thickness forming a sector of a circle, which is rigidly attached to two brush-holders and lies in a plane at right angles to the axis of the machine, so that it may press lightly against the radial edge of the commutator. The exact method of attachment to the brush-holders must be worked out for each type of brush-holder support. The point to keep in view is that, while it is convenient to have some tangential adjustment when fixing the guide-strip in position, we must be sure that after it has been tightened up no movement relatively to the brush-holders is

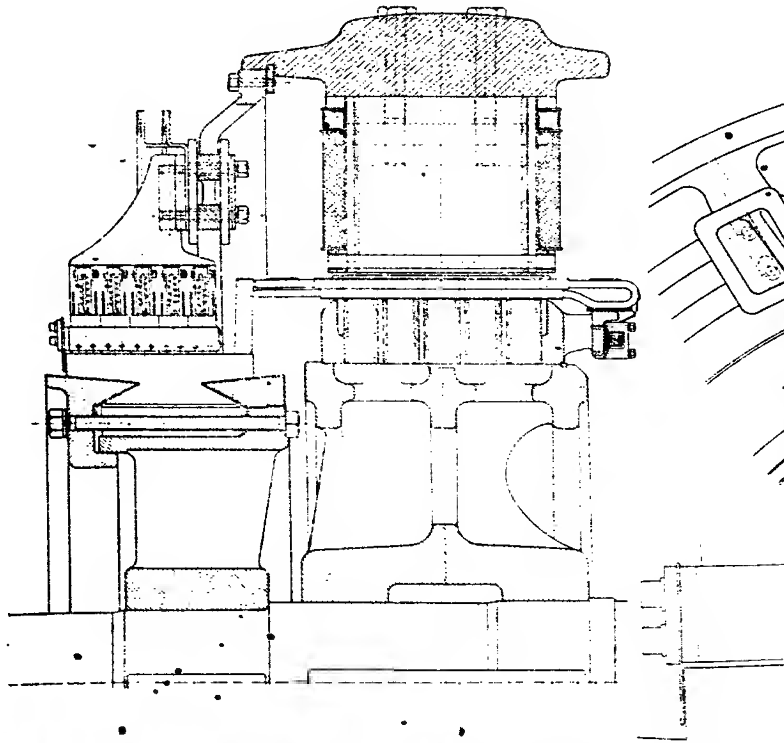


Fig. 251.—Arrangement of apparatus for taking the distribution of potential around a commutator. The guide-strip is shown on a larger scale in Fig. 252

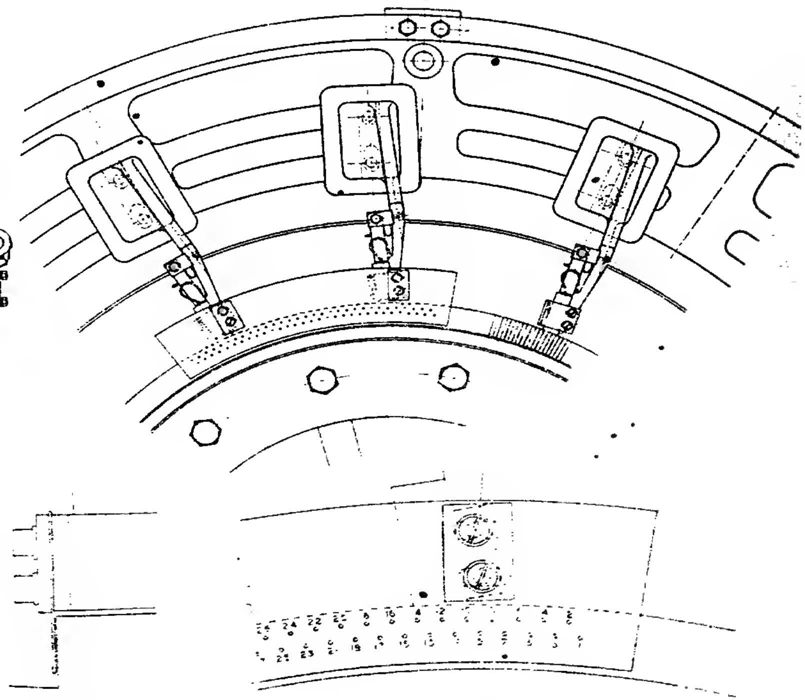


Fig. 252.

possible. The guide-strip is pierced with a number of holes of a diameter just sufficient to admit the round lead of a 4H lead pencil. These holes commonly have a pitch equal to the pitch of the commutator bars; but this is by no means necessary. The holes should lie on the arc of a circle that is exactly concentric with the centre of the machine, the position of the arc being such that the lead of a pencil inserted through one of the holes bears directly against the radial edge of the commutator. The guide-strip should be so close to the face of the commutator that the overhang of the lead of the pencil after being passed through the hole is not more than $\frac{1}{32}''$. In cases where it is desirable to make the pitch of the holes extremely small, two rows of holes may be pierced, as shown in Fig. 252. The holes should be numbered with very legible figures, so as to avoid mistakes in taking readings. A good way of arranging the lead pencil for connection to a voltmeter is shown in Fig. 253. The

FIG. 253.—Arrangement of a 4H pencil for taking the distribution of potential on a commutator.

wood is cut away so as to allow the lead to project half an inch; the insulation is removed from the end of a piece of ordinary flexible conductor, and the fine copper strands are tightly wrapped to the lead for a distance of about $\frac{1}{8}''$ by means of very fine binding wire. It is best to prepare three or four of these pencils, so as to have a spare ready in case one of the leads should be accidentally broken. It is better not to sharpen the lead, but to keep it at its full diameter with the end squared off; it can then be made to fit exactly the holes in the guide-strip.

In fixing the guide-strip, it is well to arrange one of the holes (say hole No. 10) so that it is exactly opposite to the centre of a brush or some other prearranged datum point. A record must be made of what this datum point is and of the number of the hole that is opposite to it.

Before beginning to take readings, one should see that there are no circumstances in connection with the machine that will tend to interfere with the shape of the potential curve. In particular, the following matters should be looked to:

(1) The brushes should be correctly spaced (see page 333).
(2) The brushes should be evenly ground in (see page 319).
(3) The brushes should be rocked to the desired position, and a careful record should be made of the position of the brushes with respect to the no-load neutral (see page 252).

(4) If the potential curve is to be taken on load, a record must be made of the adjustment of the commutating poles.

(5) The load should be evenly distributed between brush-arms (see page 329).

The flexible leads from the pencils are connected to the terminals of a multi-range voltmeter, such as that illustrated in Fig. 1. It is well to get into the habit of turning back, after each reading, the switch on the voltmeter that changes the range, so that the switch is normally left in a position in which it is safe to apply the pencils to any part of the machine without endangering the voltmeter During the reading the switch can be quickly turned round so that the instrument reads on the best scale, and at the same time as the reading is taken the scale of the instrument is recorded. The voltmeter should preferably have a fairly high resistance, not less than 10,000 ohms; this is necessary, because the contact resistance between the commutator and the end of the pencil will influence the reading, if it is not negligible in comparison with the voltmeter resistance. It is well to observe whether an increase of pressure of the pencil on the commutator makes a sensible change in the reading. It is desirable to have the pressure of the pencil not too heavy, or its rate of wear will be too rapid. With a high-resistance voltmeter, a steady reading can be obtained with quite a light pressure, so that a quarter-inch length of 4H pencil will last for a whole set of readings. In this connection it is worth while to take some care in the preparation of the radial edge of the commutator; it should be carefully ground smooth with carborundum paper and highly polished with glass paper.

It is convenient to begin with one pencil on the datum point and the other in the next hole to it, the second reading being taken with the first pencil at the datum point and the second pencil in the third hole, and so on. It will be found convenient to arrange the holes so that one can take readings on both sides of the datum mark without shifting the guide-strip. Care should be taken to maintain the conditions constant throughout the whole set of readings; for this purpose it is well to have an ammeter in the field circuit and to see that the current is constant. If it is impossible to keep the load constant, readings of the load current must be taken simultaneously with the voltmeter readings.

Sometimes the object of the test is to compare the potential distribution curve between one pair of brush-arms with that between another pair of brush-arms. In this case, care must be taken when moving the guide-strip to see that exactly the same datum point is taken on each brush-arm. There are two methods of using an apparatus of the kind shown in Fig. 251. According to one method one terminal of the voltmeter is connected to one of the brush-

holders and the other to a pencil which is pressed upon a point of the commutator. This gives a measurement of the difference in potential between the brush and that point of the commutator. According to the other method two pencils are used, connected to the terminals of the voltmeter and pressed upon adjacent points of the commutator, the distance between the pencil points remaining constant. The reading on the voltmeter is then proportional to the voltage between adjacent bars. When this second method is employed the sum of the individual readings should be equal to the reading obtained by placing one pencil at one end of the measured range and the other pencil at the other end. The first method will be found most convenient for taking a potential distribution curve.

Method of taking the approximate field-form.

On a lap-wound D.C. generator having a full-pitch winding, the voltage between adjacent commutator bars is roughly proportional to the flux density in the air-gap at a point where the coil between the two bars is at any particular instant. The measurement of the voltage between adjacent bars at successive points enables us to make a plot of the approximate field-form of the generator. The field-form is of course distributed by the presence of open slots, but the average flux density at any point of the field-form gives us an average voltage at that point which is proportional to the ordinate of the flux density curve. In cases where the armature coil has not a full-pitch the two coil-sides are a little out of phase and give us a blurred field-form, which is, however, often sufficiently accurate for our purpose. On wave-winding we also get a blurred field-form.

When measuring the voltage between bars each pencil should be clearly marked or coloured so that it can be instantly identified as belonging to the positive or negative terminal of the voltmeter, otherwise mistakes may be made in the polarity of the readings.

Comparison between readings on D.C. and on A.C. voltmeters. It should be remembered that the readings that are taken on the D.C. voltmeter give the *mean* difference of potential between the two pencil points. In practice, the difference of potential is rarely constant, there being an alternating E.M.F. superimposed upon the direct E.M.F., for the reasons explained in connection with Figs. 238 and 240 (and see page 342). For some purposes it is instructive to read the difference of potential between the pencil points both on a D.C. voltmeter and on an A.C. voltmeter. If the two readings are sensibly the same, it shows that there is not much alternating component in the voltage. The square of the A.C. component can

be obtained* by subtracting the square of the D.C. instrument reading from the square of the A.C. instrument reading.

MINOR DEFECTS IN DIRECT-CURRENT GENERATORS.

Failure to excite.

(1) If a D.C. generator is run for the first time and fails to excite, it may be that the **shunt coils have been connected in the wrong way.** For a given machine running in a given direction there is only one right way of connecting the shunt coils. Referring to the two-pole machine shown diagrammatically in Fig. 254, suppose that with a north pole on the right side of the armature a clockwise rotation gives positive polarity on the upper brush, then the shunt coil must be connected as shown in the diagram, so that the current from the positive brush passes round the field magnet in a way that strengthens the north pole. If the pole on the right hand were a south pole, the same direction of rotation would give negative polarity to the upper brush, and with the connection as shown the current would pass against the arrow-heads in the Fig. 254, so that the south pole would be strengthened. If, however, the shunt connections are reversed, then whatever the polarity of the magnet the current from the armature would tend to weaken the pole—that is, reduce the residual magnetism.

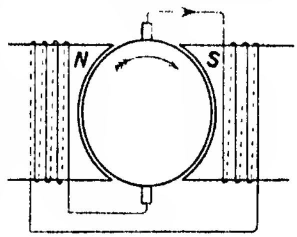


Fig. 254.

(2) **Brush holders rocked through a pole pitch.** Sometimes after a machine has been running with the shunt coil properly connected, the brush-holders have been by mistake rocked through a pole pitch so that what are the upper brushes in Fig. 254 become the lower brushes. This has the effect of reversing the shunt connections, and the machine will fail to excite.

(3) **Brushes not down.** The brushes should be carefully inspected to see that they are making good contact with the commutator and are working well in the holders.

(4) **Brushes off the neutral.** Sometimes the brushes have been rocked a long way from neutral and are in contact with armature

* The proof of this is as follows: Let the voltage vary as $A+B\sin\omega t$. The A.C. instrument reads the square root of the mean square of this, or

$$\frac{1}{2\pi}\int_0^{2\pi}(A^2+2AB\sin\omega t+B^2\sin^2\omega t)\,dt=\sqrt{A^2+\tfrac{1}{2}B^2}.$$

The D.C. instrument reads only A, so that the difference of the squares gives $\frac{1}{2}B^2$.

coils passing under the main field. If the brushes are rocked forward the current in the coils short-circuited by the brushes will have a demagnetizing effect upon the magnet and oppose the excitation of the machine. If the brushes are rocked a little back from the neutral the current in the short-circuited coils has a tendency to assist the excitation.

(5) **Resistance in field circuit too high.** To make a machine excite as quickly as possible the rheostat should be put in the "all out" position. It has been shown on page 244 that there is a critical resistance in the shunt circuit above which the generator will not excite when running at a given speed. Even when the sum of the rheostat and shunt-coil resistance is well below the critical value, the machine may fail to excite, on account of the virtual high resistance of the brush contact. This is explained more fully on page 247. The difficulty does not occur unless the residual magnetism is very low.

(6) **Shunt coil open circuited.** If the matters mentioned in the preceding five paragraphs are in order, and the machine still fails to excite, it is necessary to make an examination of the exciting circuit and see that there is no break in it. One way of checking this is to connect a low-voltage battery in circuit with it and see whether any current passes. Current will be indicated by a spark on account of the high self-induction of the shunt coils. In connecting the battery one should see that it is connected in so that it tends to help the residual magnetism and not to reverse it. For this purpose one should definitely ascertain which end of the shunt circuit is intended to be positive and connect in the battery accordingly. The methods of finding a fault in any circuit have been discussed on pages 36 to 40.

(7) **No residual magnetism.** It sometimes happens that by some accident the residual magnetism of machines has been reduced so nearly to zero that the effect described on page 247 prevents the machine from exciting. The connecting in of a battery as described in the last paragraph, especially if it is kept in circuit while the machine is run, will give sufficient magnetism to overcome this defect. As soon as the machine begins to build the battery should be taken out of the circuit. Where there is voltage available from other machines, it is of course possible to pass the current through the shunt coils from the busbars, care being taken to preserve the right polarity of the machine.

(8) **Field coils wrongly connected.** It may be that on a two-pole machine the two shunt coils are connected in series so that they oppose one another. This is a matter that is easily checked and rectified.

If on a four-pole machine one of the shunt coils is reversed, the

effect will be to so lower the voltage generated by the brushes that the resistance of the shunt circuit will probably be above the critical value, and for that reason the machine will fail to excite.

If all matters covered by the seven preceding paragraphs are in order and the generator still fails to excite, current should be passed through the shunt coils and their polarity observed, and if necessary corrected.

(9) **Armature short-circuited.** If there is any serious short circuit in an armature, the current set up when it is rotated in the magnetic field will tend to demagnetize the field. The coils that are short-circuited will rapidly heat up. See pages 30 to 36.

Wrong polarity.

The polarity with which a generator will build up will depend upon the polarity of the residual magnetism. After a machine has been in service it is usually found to retain its residual magnetism in one direction, so that when it is run up to speed the brushes have the desired polarity.

(1) It may be, however, that by some accident the **residual magnetism** has been **reversed.** This sometimes happens on a generator provided with a series winding on the field-magnet after a short circuit has occurred and the breakers of the station have come out. Where there are several machines running in parallel those machines which have for the moment the greatest amount of stored energy in the series coils may discharge their current through other machines having a less amount of stored energy. In the case of rotary convertors on short circuit there are other reasons for reversible polarity, as mentioned elsewhere.

(2) **Brushes rocked through a pole pitch.** Sometimes the brush rocker and connecting leads are so constructed that it is possible to rock them through more than a pole pitch. It may be that an attendant in cleaning or grinding in brushes has rocked the holder as far as it will go in order to get at brush-holders otherwise inaccessible. Sometimes it is found that the reversed polarity of the machine is due to the brush-holders having been left in this position. This can only happen if the shunt circuit is fed directly from the busbars. If the shunt current is connected to the brushes the machine will refuse to excite until the brushes have been rocked to their normal position.

Insufficient voltage.

The causes which may lead to the generation of insufficient voltage by a D.C. generator are in general the same as those considered on page 190 with regard to an A.C. generator. When a D.C. generator running at its proper speed and fully excited generates

only about one-half of its rated voltage, it may be that the armature had been wrongly connected up, coils that are intended to be in series having been placed in parallel. For instance, a four-pole armature intended to be connected up as a two-circuit winding with one idle coil may by mistake be connected up as a four-circuit winding.

The first step is to make quite sure that the field-magnet is fully excited, and that all the exciting coils are properly connected. It is a fairly simple matter to check the polarity of the poles (see page 191) and to trace out the shunt connections. The exciting current should be measured and checked from any available data.

The next step is to take a no-load magnetization curve by running the machine at full speed and measuring the voltage generated at various field currents, care being taken that the brushes have been placed upon the neutral line (see page 279). The question whether the iron of the frame is approaching the magnetic saturation at the higher voltage generated by the machine can be judged by plotting the magnetization curve. If it is found that saturation sets in at about half the rated voltage, there is strong evidence that the armature is at fault. The best plan, then, is to make a thorough test of the armature circuits, as described on pages 18 to 26.

If the voltage generated is much more than half, but is limited by the saturation of the iron, so that it does not reach the full rated value when the field current has been brought up to its full value, this may be due to any one of the following causes:

(*a*) Defect in the magnetic circuit.
(*b*) Wrong armature having been inserted by mistake.
(*c*) Wrong field coils having been put upon the poles by mistake.

(*b*) and (*c*) can be checked by taking the resistance of the armature and of the field coils and checking them from the designer's data.

(*a*) The defect in the magnetic circuit may consist either in the air-gaps being too great, or in insufficient iron having been provided, or in the quality of the iron being lower than was expected. The air-gap should be measured, and the dimension checked from the designer's data. If insufficient iron or poor quality of iron has been supplied, this is a matter which can in general only be remedied by rebuilding the machine.

In cases where bolted-on poles have been employed, it is possible to obtain a little more voltage by putting liners under the poles so as to reduce the air-gap. Where liners cannot be put under the poles, it is sometimes possible to rivet thin iron plates to the pole faces. This is a matter which should only be attempted with the consent of the designer of the machine; and it must be carried out in a very sound mechanical manner, so that there is no chance of the plates coming loose. Any loose pieces of iron in the air-gap are

a source of great danger to the armature. Where it is impossible to reduce the air-gap, it is sometimes possible to slightly widen the pole face. This is also a matter which must be referred to the designer and carried out with the very greatest care in mechanical construction. Where the saturation occurs in the pole shanks, it is sometimes possible (in cases where the shunt coils are large enough) to flank the pole faces with sheet metal so as to increase the cross-section of the pole. Here, again, great care must be taken in deciding upon the method of fixing the iron, so as to avoid injury to the field coils.

Where the machine is self-excited, any defect in the magnetic circuit gives rise to a greater deficiency in voltage than if the machine were separately excited, because the reduction of the voltage leads at the same time to a reduction of the field current.

In cases where the resistance of the shunt coil is such as to make the resistance line, Fig. 230, almost parallel to the straight part of the magnetization curve, this characteristic of the self-excited machine may lead to a very considerable drop in voltage, although the defect in the magnetic circuit is only a small one.

The reduction of the air-gap or the addition of a little more iron to the magnetic circuit may make a very great difference to the voltage generated, as can be seen from pages 244 and 247.

Defective shunt coils. Sometimes the wire used in winding the shunt coils is of slightly higher resistance than was intended. This leads to a steeper resistance line (Fig. 230), and may in certain cases result in quite big deficiencies in the voltage generated. Sometimes the voltage is sufficiently high when the machine is cold, but falls below the rated value when the machine is hot, owing to the increase of resistance in the shunt coils. This defect is emphasized in the conditions mentioned in the paragraph above, and may be due to the poor cooling conditions of the shunt coils. If the cooling conditions cannot be sufficiently improved, the best cure is to wind new shunt coils with wire of larger section.

Poor insulation between turns.

Generators that have shunt coils wound with cotton-covered wire, which have been standing in a damp situation for some time, may have insulation between turns so far reduced that the whole of the current applied to the shunt coil does not go through the total number of turns but leaks through the insulation from layer to layer, so that the magnetizing effect of the coil is very much reduced. The defect is a difficult one to diagnose, unless a record has been kept of the original resistance of the shunt coils. Where it is suspected, the resistance of each shunt coil should be separately measured, and checked with the resistance of similar shunt coils

that may be in the possession of the user. The best cure is to have the coils thoroughly dried out in a vacuum oven and impregnated with petroleum residue.

Too high voltage.

Sometimes when a machine is run at its proper speed and normal excitation it is found that the voltage generated is about twice as high as was expected. This may be due to the armature being improperly connected. Where an armature has been constructed with a duplex winding it may very easily be connected up by mistake as a simplex winding giving double the voltage. The resistance of the armature should be measured and checked from the designer's data.

Instability of voltage.

A trouble which is sometimes met with on D.C. generators is the variation of the voltage from time to time, which causes an unsteadiness in the lights; or if the generator is the exciter of an alternator it may lead to unsteadiness in the A.C. voltage. The causes giving rise to this instability of voltage may be classified under the following headings:

(1) Small changes of speed.
(2) Changes in brush-contact resistance.
(3) Changes in facets of the brushes.
(4) Changes in the resistance of the shunt circuit.
(5) Bad contacts in the armature circuit.

(1) By attaching a tachometer it is easy to ascertain whether the fluctuations in voltage are due to fluctuations in speed. Where a machine is working on a point of the saturation curve, such that the line representing the resistance of the shunt circuit (Fig. 230) is almost parallel to the straight part of the magnetization curve, very small changes in speed may lead to very great changes in voltage. This defect is not uncommonly met with on the exciters of A.C. generators. The author met with a case in which very slight hunting of the governor, only discernible on a sensitive tachometer, led to a serious fluctuation in the A.C. voltage of the generator, owing to the fact that the exciter was working upon an unstable part of the magnetization curve. The cure in this case was to give greater stability to the exciter.

(2) It is sometimes found that the brushes of a D.C. machine change their resistance from time to time, owing to changes in temperature or to small variations in the mechanical working of the brush-holders. Such small variations would generally be of no importance, if they were not aggravated by some instability in

the machine, owing to its working upon an unstable part of the magnetization curve. Sometimes the whole brush-holder support has not been properly secured, and the vibration causes a continual change in the brush resistance.

(3) As will be seen on page 252, the voltage of a D.C. generator depends upon the position of the brushes. If the brush-holders are defective, it is sometimes possible for a carbon brush to change its facet in an erratic manner, sometimes bedding on the toe, sometimes bedding on the heel. This amounts virtually to a change in the brush position, which will lead to an erratic change in voltage, especially where the generator is operating upon the unstable part of the magnetization curve.

(4) Sometimes there is a loose contact in the exciting circuit; it may be on the rheostat switch or inside the rheostat or in the connections of the shunt coils. The field circuit should be carefully traced through, and all contacts made mechanically strong. It not uncommonly happens that an insulated wire has a break in the copper which is invisible, because the ends of the wire are held together by the insulating covering. A shaking of the wire will cause a variation of the current in the circuit.

(5) If a loose contact occurs in the armature circuit or field coils, the circuit should be tested in the manner indicated on pages 36 to 40.

Stability plate.

Where it is desired to give a generator a very wide range of voltage adjustment by variation of the shunt excitation, there is a danger that at the lower voltages the generator may be working on an unstable part of the magnetization curve. In order to give as great stability as possible at the lower reaches of the curve, it is a good plan to insert in the magnetic circuit what has been called a "stability plate." This consists of an iron plate, having a cross-section considerably less than the cross-section of the pole, which is inserted between the back of the pole and the yoke so as to form part of the magnetic circuit (see Fig. 255). The thickness of the plate and its cross-section in relation to the cross-section of the pole are adjusted so that if the plate consisted entirely of non-magnetic material the reluctance of the air-gap at the back of the hole would be such as to call for a fairly high magnetizing current at the highest voltages generated by the machine. The introduction of a small bridge of magnetic material across this gap makes it possible for the field flux to increase rapidly for small values of the exciting

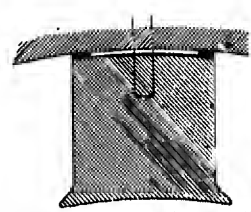


FIG. 255.—Showing "stability" plate behind pole piece.

current, while for larger values the slope of the saturation curve becomes almost the same as if it were not present. A simple way of judging the effect of the bridge-piece is to plot two magnetization curves, one for the magnetic circuit of the generator on the assumption that there is no stability plate, and another magnetization curve that relates to the bridge-piece only. It is convenient to take as ordinates for these curves the flux per pole, and as abscissae the ampere-turns per pole. Curve A, Fig. 256, gives the relation between

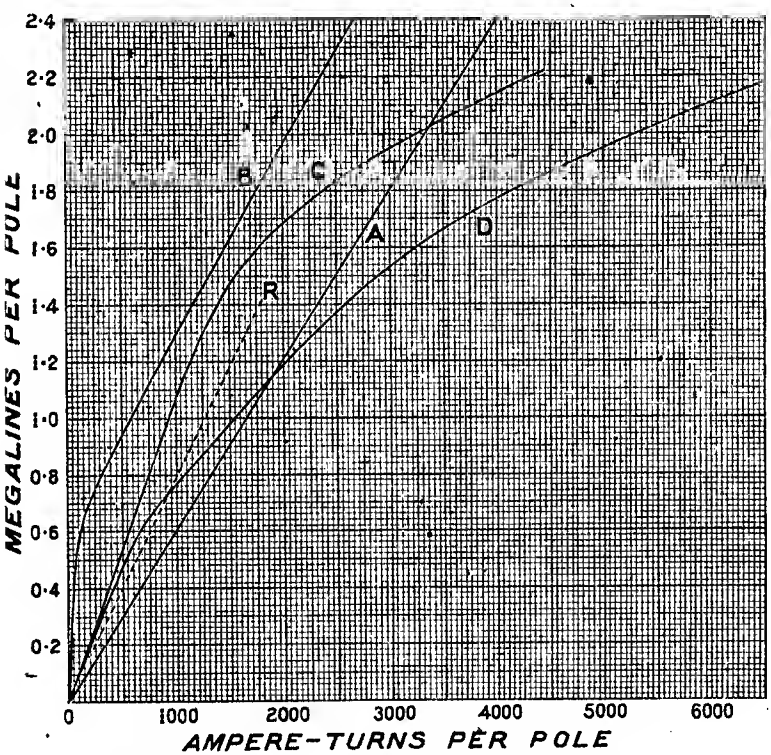


FIG. 256.—Magnetization curve of generator fitted with "stability" plate.

the flux per pole and the ampere-turns on the air-gap behind the pole, on the assumption that the bridge-piece is not present and that the whole of the flux has to go through the air-gap between the back of the pole and the yoke. The curve in Fig. 257 shows the relation between the flux carried by the bridge-piece and the ampere-turns applied to the bridge-piece. Curve B in Fig. 256 is formed by the addition of the ordinates of A and of the curve in Fig. 257. It is therefore the magnetization curve of the stability plate and air-gap behind the pole. If now curve C is the magnetization curve of

the machine, as it would be without the stability plate, we may by adding the abscissae of B to those of C obtain the curve D which gives the real magnetization curve of the machine.

The cross-section of the iron of the stability plate is adjusted so that for the lowest voltages intended to be generated by the machine it is just beginning to be saturated; but at these low voltages it so far reduces the reluctance of the magnetic circuit

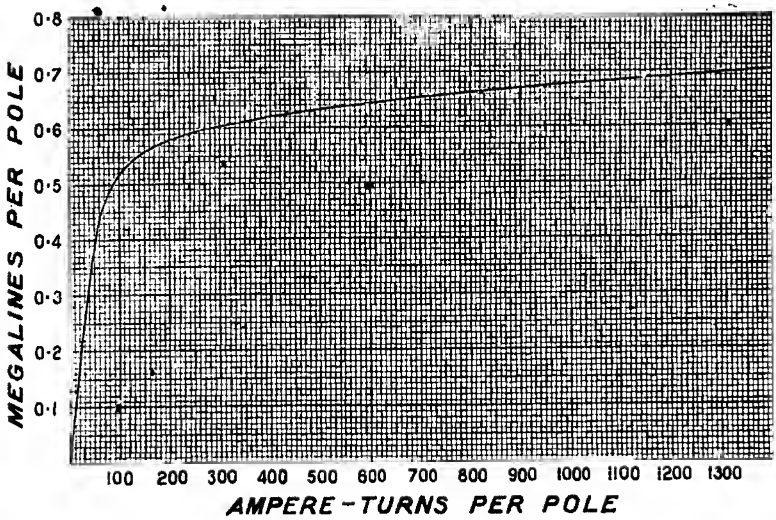


FIG. 257.—Saturation curve of "stability" plate.

as to give the magnetization curve, as it starts from zero, a much steeper slope than the curve A. Then, as the iron of the plate saturates, the curve bends over, producing a knee below the knee of the curve C. Thus at the lowest voltages there is sufficient curvature to give in the magnetization curve a precise point of intersection with the line OR which represents (see Fig. 230) the resistance of the field circuit. As long as the lower part of the line OR lies below the curve D the machine is stable, and the point of intersection gives the point to which the magnetization will rise for any given resistance in the field circuit.

CHAPTER IX

SPARKING AT THE BRUSHES

SPARKING at the brushes may be caused either by defective collection of current or by defective commutation. The commutator and brushes have to perform two functions: (1) To take up and put down the current between the stationary brushes and the revolving machine. This function is what we call collection; (2) to change the direction of the current in the coils that are for the time being passing the brushes. This we speak of as commutation.

COLLECTION OF THE CURRENT

Defects in the commutator.

With modern machines more trouble is experienced from defective collection than from defective commutation, so that one of the first duties of an engineer who is called in to find out why the brushes are sparking is to ascertain whether the surface of the commutator and brushes and the behaviour of the brushes are such as to permit of good collection of current.

Eccentricity. A cylindrical commutator should have a true cylindrical surface revolving about its centre. In actual practice one very often finds that commutators are slightly eccentric. This does no great harm in machines of moderate speed if the brush gear is properly designed, because the brushes in rising and falling as the commutator goes round at a speed of from 10 to 15 revolutions per second can keep in close contact with it. In turbo machinery, where the revolutions are 50 or more per second, good contact cannot be secured unless the eccentricity is extremely small.

Wavy surface. One sometimes finds that the commutator has a wavy surface, there being many ups and downs in one revolution. This causes very much more trouble on commutators of moderate speed than a small eccentricity, because, in order to follow the surface, the brushes must move up and down at a very much greater frequency. Sometimes this wave formation appears when the com-

mutator is hot and disappears when the commutator is cold. One cause of this is the building of the commutator on the arch-bound principle. The way in which the bars on a commutator are secured is of great importance in obtaining satisfactory operation. Some years ago it was the opinion of many builders of commutators that the right way to hold the bars was to build them up in the first instance with the micanite insulation between them and subject the whole commutator to a very great radial pressure from the outside inwards while it was heated up, so as to squeeze out as far as possible all free shellac from the micanite. When the commutator was in this highly compressed condition the *V*-grooves were turned true, the mica *V*-rings were inserted, and the steel *V*-ring was adjusted to such a size that its inside conical surface pressed against the inside conical surface of the copper. Matters were arranged so that, however tightly the *V*-ring was pressed in, it pressed against the inside conical surface rather than the outside conical surface, so that each bar was held from coming outwards by the *V*-ring and from going inwards by circumferential pressure against other bars. Such a commutator is said to be "arch-bound," because each bar is secured by circumferential pressure like the stones in the arch of a bridge. The objection to this way of building a commutator is that when the copper gets hot it cannot expand in a circumferential direction without stretching the steel *V*-ring, so that it brings enormous pressures to bear upon the mica segments; and as these segments are not of absolutely uniform character, some of them may give a little on the sides nearer the centre and others on the sides furthest away from the centre, with the result that the commutator takes up a wavy outline on what ought to be a cylindrical surface. As the commutator is usually turned true while it is cold and the wavy outline only appears when it is hot, the ordinary trueing-up process does not get rid of the trouble. The frequency of the wave may be so high that a very small wave amplitude is sufficient to cause trouble. It is therefore sometimes exceedingly difficult to see what the sparking is due to.

According to the other method of building a commutator, the steel *V*-rings are made of such a size that when they are tightened up into the *V*-grooves they press as much against the outer conical surface as against the inner conical surface; that is to say, they have no tendency to increase the tightness of the arch. In building up a commutator on this plan it is well to see that the mica segments are not too severely pressed during the process of assembling the commutator. It is sufficient to put just enough pressure on them to prevent the mica from being thrown out by centrifugal force. The *V*-groove is then turned up to fit the commutator in this state, and after the *V*-rings have been put into place they nip each bar

independently by the V-groove, and the support of the bar is independent of the tangential pressure between bars. A commutator built in this way may be said to be "nip-bound" as distinguished from "arch-bound." The advantage of building a commutator in this way is that when the copper expands it can do so in a circumferential direction without causing any excessive circumferential pressure, the expansion in a longitudinal direction being taken up by the elastic stretching of the long steel bolts. That this is possible will be seen from the following example :

EXAMPLE. In the commutator illustrated in Fig. 251, the length of the copper between the two points of the V-rings is 10 cms. and the length of the steel bolts is 33 cms. Even if we allow a temperature rise of the copper of 100° C., while the bolts remain cool, the coefficient of expansion of copper being 0·0000166 the actual expansion assuming no restraint will be only 0·016 cm. Assuming that the bolts are stretched by this amount (in practice they will be stretched less than this, because the copper will be under some compressive stress), the strain will only be $\frac{\cdot 016}{33} = 0{\cdot}0005$. Taking the modulus of elasticity of the bolts at 30×10^6 in inch-lb. units this strain would give a stress of 15,000 lbs. per sq. in., or 1050 kilograms per sq. cm. This is well below the elastic limit of the material

High bars. It sometimes happens that, after a commutator has been run, some of the bars are not held in place sufficiently well by the mica V-ring, and are driven out a few thousandths of an inch by the centrifugal force. High bars can generally be detected by the noise they make in striking against the brushes or by the slight difference in colour they present owing to the wear on their surface. If the bars finally become fixed in position, it is possible to grind them down and get rid of the defect.

Low bars. Sometimes a few bars are lower than the rest of the commutator and cause trouble, owing to the fact that the brushes do not come in contact with them as they pass the brush arms. Low bars are very much more difficult to get rid of than at first might be supposed, because the ordinary commutator grinding tool has a certain amount of "spring" in it ; and after a commutator has been ground all over and shows a surface completely polished by the grinding wheel, the low bars may nevertheless be still causing a slight hollow that is not apparent to the mechanic who is doing the grinding. Any low part of the commutator of this kind is almost certain to become worse when the commutator is in operation. It does not disappear, as one might naturally suppose, by the mechanical wear of the commutator against the brushes. The *mechanical* wear of a copper commutator against carbon brushes is extremely small. The actual wear that occurs in practice is very seldom mechanical, but is a process ot electrical attrition due to particles of copper being thrown from the surface of the commutator when the current passes between the commutator and the

brushes. The rate at which this electrical wear takes place depends upon the length of the arc between the commutator and the brushes; and where the arc is very short, say not more than ·0001″, the rate of attrition is small. If the distance between the brush and the commutator is of the order of ·001″, the electrical wear becomes much more marked. If, therefore, there are any low bars (not so low that they break contact with the brushes altogether), the disappearance of copper from the surface of those bars is greater than from the rest of the commutator surface, so that low bars always tend to perpetuate themselves, and the low part on a commutator tends to spread on account of the bad contact that it causes between the brushes and adjacent bars. What is sometimes called a " flat " on a commutator may be due to nothing more than an accidental lowness of some of the bars, which tends to perpetuate itself and to spread notwithstanding frequent attempts on the part of the commutator grinder to get rid of it. Where the " flat " does not arise from any other cause it can be completely got rid of by fixing the grinder very rigidly and feeding the grinding tool very lightly while traversing the surface of the commutator several times. The " flat " may, of course, arise from some defect in the armature, which throws on to one or two bars a very much heavier current than the normal.

High mica. After a commutator has been ground true and put into service, it may be found that the mica segments are higher than the commutator segments by an amount which is hardly measurable by any ordinary instrument, but which nevertheless prevents the brushes from making proper contact with the copper segments. The fact that the brushes are a few ten thousandths of an inch away from the copper brings about the electrical wear mentioned above, so that the protrusion of the mica becomes aggravated and the commutator grows gradually worse. So much trouble has been experienced from this defect that many manufacturers cut out the mica between the segments for a depth of about $\frac{1}{32}$″. This has the desired effect of preventing the high mica, and interferes only very slightly with the smooth running of the commutator. Twenty years ago, when softer micas were procurable in commercial quantities, this trouble was not so commonly met with; and it is still believed that there are micas whose softness is such that the mechanical wear between the mica and the brushes can keep pace with the wear between the brushes and the copper. In all cases, however, where a doubt exists as to whether the mica is high or not, the best plan is to have it cut out and eliminate that possible cause of trouble.

Soft copper. Most engineers who have had experience with the manufacture of commutating machines have met with the phenomenon commonly spoken of as " soft copper.". No one seems to know

what the cause of the phenomenon is, but the trouble that arises from it is unmistakable. It begins to make itself apparent by the appearance of copper on those brushes to which the current flows from the copper of the commutator. The smudging of copper off the commutator on to the brushes may, of course, occur under various conditions, and may be not at all due to the phenomenon now under consideration. But there are cases where it can apparently be attributed to no other cause. The smudge of copper on the brush gradually accumulates more metal, until it forms a minute scale, which is dragged off the brush and thrown off into the air. Thousands of these little scales are produced when the machine is on load, and collect as a fine powder on the brush-holders, bed-plate and surrounding floor. If the machine is running without load or with very little load, these scales are not produced even though considerable mechanical pressure is used between the brushes and the commutator. It can be definitely proved that "soft copper" is not due to any mechanical cause and is not due to any mechanical *softness* of the copper in the sense of ductility. The effect seems closely allied to the electrical wear described above, and differs from it in that it occurs notwithstanding the closest possible contact and perfect working of the brush-holder. It seems to be due to some physical or chemical state of the copper, and the following possible reasons have been suggested: (1) It may be due to the mechanical breaking up of the copper crystals during the process of drawing the bar through a die. It is well known that when a newly-made commutator is turned on a lathe the way in which the copper turnings come off from it is quite different from the way in which the turnings come off an old commutator that has seen many years of service. This points to a difference in the structure of the metal in the two cases. It may be that in the many heatings and coolings of the machine in service the structure of the metal undergoes a change. (2) It is known that electrolytic copper contains a certain amount of hydrogen. The presence of this hydrogen may effect the structure of the metal, or at any rate its behaviour when current is passed from it to a carbon brush. (3) Electrolytic copper sometimes contains small traces of sodium, and this may possibly affect the structure or the electrical wear.

One remarkable thing about the "soft copper" phenomenon is that it invariably disappears of its own accord when the machine is kept in service for a number of months. All sorts of different carbon brushes may be tried; all sorts of adjustments of commutating poles and brush positions may be tried, each one of which is alleged to produce some improvement. After working through every kind of carbon brush and making every likely adjustment, if, in about six months time, the experimenter works round to the same carbon

brush and the same electrical adjustment as he had to begin with, he will generally find that the "soft copper" has cured itself. This goes to prove that it is due to some peculiarity connected with the structure of the metal.

Unseasoned commutators. All commutators that are insulated with micanite should be properly seasoned before leaving the makers' works. The seasoning process consists in raising the commutator to a temperature between 100° and 120° C., and while it is hot running it at a speed a little above the normal. This process has the effect of driving out by centrifugal force all bars that can move, either on account of thin places or of pockets of shellac in the mica *V*-rings.

Where a commutator has not been properly seasoned, the symptoms that appear are the following: After it is turned true it operates quite well for a short time, and then shows a certain amount of sparking. The surface is patchy in colour, some parts being darker than others. It is not always possible to see that some bars are high and some low, there being just enough difference in height to give a difference in colour to the surface of the bars. If nothing is done and the sparking gets worse, the bars that are low become lower through the action described on page 298. If the commutator is turned up again, it will work well for a few days, and then the trouble begins again, so the thing may go on for several months. The best way to get rid of the trouble is to make arrangements for heating up the commutator either by means of a gas ring, or failing that, a number of blow torches may be used. While the commutator is being heated up it should be turned round very slowly either by hand or by being belted on to a motor arranged to turn it at a speed of not more than 1 ft. per second. If too high a speed is used for turning the commutator while it is being heated, the windage caused by the commutator necks will carry away the heat and make it very much more difficult to reach the required temperature. Arrangements must be made so that as soon as ever the commutator reaches the temperature of 110° C., the machine can be run up at full speed or preferably 10 per cent. over speed, the full speed being reached before the commutator has appreciably cooled down. It is well to repeat the process two or three times in order to make sure that all the bars are thrown out to the limit of their possible motion. Sometimes after this seasoning process high and low bars are visible to the eye, there having been a movement of a few thousandths of an inch. The commutator is then allowed to cool down and is turned and ground. In grinding, great care should be taken that the "spring" of the grinding wheel is as small as possible. At least three very light cuts should be taken over the whole surface of the commutator.

The looseness of supports. The whole spider on which the commutator is built may be insecurely supported on the shaft or other part to which it is attached. This may bring about shifting of the commutator and consequent defective collection of current.

Skewed bars. A defect which does not interfere with the collection of current but may affect the commutation is a want of parallelism between bars in the direction of the axis of rotation. It sometimes though rarely, happens that a commutator has been built up with the bars slightly skewed, that is not parallel to the centre of the shaft. This will not do very much harm if all the bars are skewed the same amount, because it can be allowed for in setting the brushes; but if the skewing is irregular the commutator should be rebuilt.

Symptoms of defective commutator surface.

Where the average distance between the copper and the carbon brush is greater than it should be, owing to defective commutator surface or other reason, the drop in potential between the brush and commutator is greater than it ought to be. Increased brush drop is one of the most certain symptoms of this defect. This leads us to consider brush drops in general. **The voltage drop between the carbon brushes and the commutator** under normal conditions depends mainly upon three factors: (1) The quality of the brush; (2) the current density; and (3) the pressure of the brush against the commutator.

Characteristics of carbon brushes.

The carbon brushes on the market are very various. It is not proposed here to consider their qualities at great length. They may be broadly divided as follows:

(1) Ordinary carbon brushes. These are of varying hardness. At one end of the scale is retort carbon, at the other a softish mixture of carbon and graphite.

(2) Graphitic brushes, whose structure is soft enough to mark on paper like a blacklead. These are of several sorts: the electro-graphitic brushes, made from carbon, which is afterwards converted into graphite in an electric furnace; burnt graphitic brushes that have been made at a high temperature; and the compressed graphitic brushes like the Morganite, which are made by subjecting graphite to a great pressure in a mould; and

(3) Carbon-metal brushes, which consist of a mixture of carbon or graphite and metal powder.

Between (1) and (2) we may have all possible gradations in softness. As a rule, a hard brush has a higher contact voltage drop

than a graphitic brush, but some graphitic brushes have a much higher voltage drop than others (see Fig. 264). The carbon-metal brushes have low voltage drops.

Voltage drop at various current densities. Brushes for higher or lower voltage drop or of lower or higher friction coefficients can be obtained from most of the brush manufacturers. Taking a brush of medium hardness with some graphite in its constitution, the way in which the brush drop varies with the current density * is shown in Fig. 258. It will be seen that the brush drop when the current

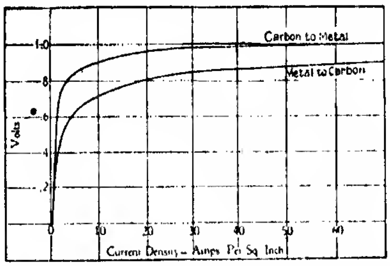


FIG. 258.—Giving the approximate drop at brushes under good conditions with ordinary carbon brushes.

goes from carbon to copper is higher than when the current goes from copper to carbon. It will be seen, too, that after the current density is increased beyond 40 amperes per square inch, the brush drop increases very slowly and tends to become constant at high current densities. At low current densities it is not possible to make any definite statement as to the amount of brush drop, because it is so much affected by the state of the commutator and brush. Where both brush and commutator are extremely highly polished, the voltage drop remains a finite amount down to the very lowest current densities; but if there is any roughness on the commutator or grittiness in the brush, tending to bring about intimate contact at minute points, the brush drop at low current densities may fall almost to zero.

In a paper† on carbon brushes, Mr. P. Hunter-Brown has given some very useful curves relating to the characteristics of carbon brushes. Some of these are reproduced in Figs. 259 to 263. Fig. 259 gives the sum of the contact drops on positive and negative brushes containing no graphite, the pressure being 2 lbs. per square inch. According to this curve, the sum of the pressures does not fall below 0·7 of a volt for exceedingly small current densities. Fig. 260 shows how the sum of the contact drops changes with the speed of the commutator. The increase of the contact drop may

* Arnold and La Cour, *Trans. Internat. Elec. Cong.*, 1904, p. 801.

† *Journ. Inst. Elec. Engrs.*, vol. 57, page 193, 1918.

be due to the drawing in of a film of air between the commutator and the brush; this theory is borne out by the fact that the coefficient of friction falls lower and lower as the speed is increased. Fig. 261 shows how the sum of the contact drops changes with the pressure on the brush: the brush in this case was one containing

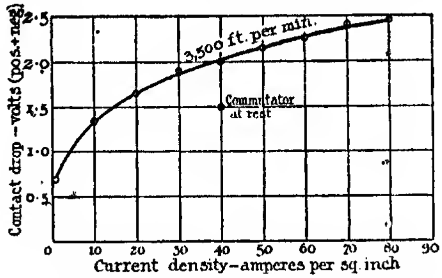


FIG. 259.—Contact drop of carbon brushes containing no graphite. Pressure 2 lb. per sq. in.

no graphite; the current density was 40 amperes per square inch and the speed 3500 feet per minute. Fig. 262 shows the difference in the characteristics between a pure graphite brush and a copper-graphite brush. Fig. 263 shows how the wear of the commutator and the brush depends upon the current density. In this figure the term "positive brush" is used in the sense in which it would

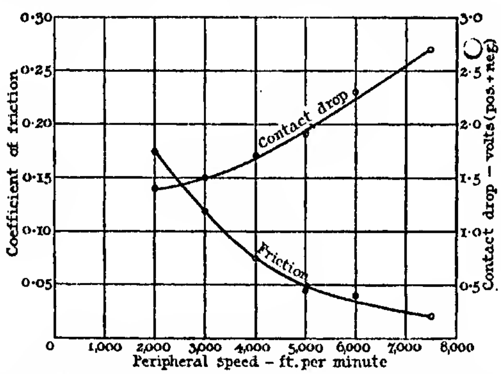


FIG. 260.—Change with speed of coefficient of friction and contact drop at 40 amperes per sq. in. of a pure graphite brush. Pressure 2 lb. per sq. in.

be applied to a D.C. motor—that is to say, current is being passed from carbon to copper; the negative brush is one in which the current is passing from copper to carbon. It will be seen that the wear on negative brushes on a motor is very much greater than on positive brushes. The wear on the commutator produced by the negative brushes is also greater than for the positive brushes.

Fig. 264 gives the mean contact drop for various grades of brushes. The ordinates of the curves give half the value of the total drop on positive and negative brushes as measured on a short-circuited

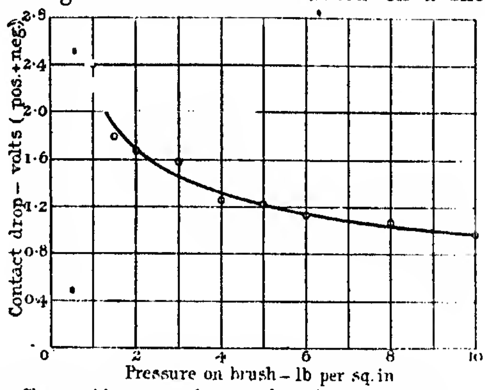


Fig. 261.—Change with pressure of contact drop of brush containing no graphite. Current density 40 amperes per sq. in. Speed 3500 per min.

commutator, running smoothly at a speed varying between 1500 and 3500 feet per minute. Between these limits the brush drop is almost independent of speed. The pressure on the brushes was 2 lb. per square inch. In the case of the carbon and graphite brushes it

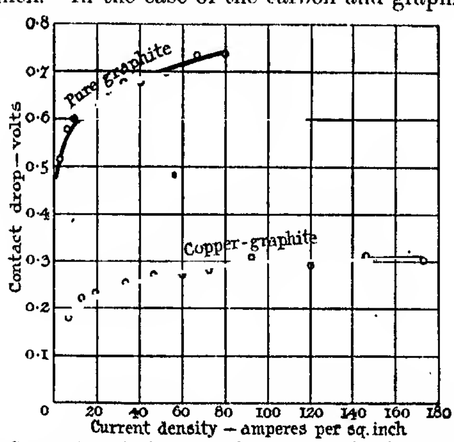


Fig. 262.—Contact drop of a highly metallic copper-graphite brush and of a pure graphite brush. Speed 4500 ft. per min. Pressure 2 lb. per sq. in.

will generally be found that when current is passed from copper to carbon the drop is from 0·1 to 0·3 volts less * than when current is

* The difference in the drop found on positive and negative brushes is very uncertain in amount and depends greatly on the state of the commutator. Mr. Hunter Brown says that he has even known the copper-to-carbon drop to be greater than the carbon-to-copper drop. This is not the experience of the author.

passed from carbon to copper. To get the drop on the positive (carbon and graphite) brush of a generator subtract 0·1 volt from the ordinate in Fig. 264, and add the drop in the brush itself worked out from its specific resistance. The specific resistance (in ohms per inch cube) of the brush material as given by the makers in their

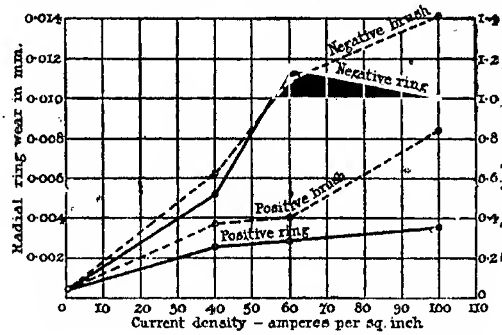


FIG. 263.—Wear of slip-ring and carbon brush containing no graphite, pressure 4 lb. per sq. in.

trade catalogue varies from 0·0004 for pure graphite brushes to 0·002 for ordinary carbon containing some graphite, and may be as high as 0·003 for some carbon brushes. The ohmic drop in an ordinary brush worked at 40 amperes per square inch may be about 0·2 volt or about one quarter of the contact drop. This must be added to the contact drop given in Fig. 264. The contact drop under practical conditions on a carbon or graphite brush carrying current from carbon to copper may be taken from 0·1 to 0·3 volt higher than the ordinate given in Fig. 264.

The way in which the pressure upon the brush affects the brush drop at different current densities is exhibited in Fig. 272.

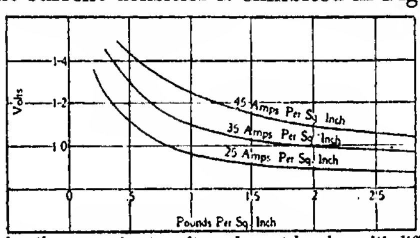


FIG. 272.—Giving the approximate voltage drop at brushes with different pressures and different densities.

The amount of brush drop is also affected by temperature. This matter is sometimes complicated in practice by the effect of the temperature in distorting the commutator; but putting this factor out of account, increase of temperature of the brush reduces the voltage drop, and this circumstance will sometimes lead to

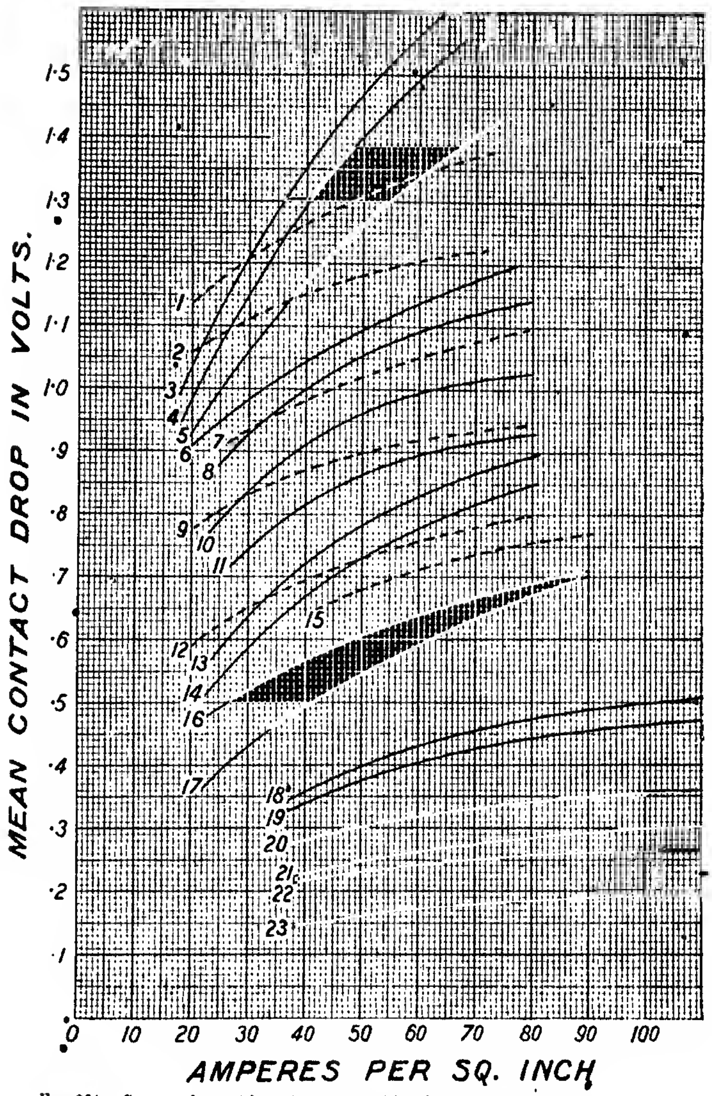


FIG. 264.—Contact drop with various types of brush (mean drop on positive and negative).

1. Battersea link C 8.
2. Battersea link C.
3. Spear 2 treated.
4. Le Carbone S4.
5. Spear 2 dry.
6. Battersea link A.
7. Hard-Morganite HM.
8. Le Carbone S 2.
9. Morganite link 2.
10. Le Carbone S.
11. Le Carbone GS.
12. Morganite link 1.
13. Le Carbone Z.
14. Le Carbone LFC.
15. Morganite CM 9.
16. Le Carbone LFC 3.
17. Le Carbone LFC 2.
18. Morganite CM 6.
19. Le Carbone KK III.
20. Morganite CM 3.
21. Le Carbone KK IV.
22. Morganite CM.
23. Metite.

instability in the distribution of current between a number of brushes working in parallel (see page 327).

The fact that the voltage-drop at the contact between carbon and copper does not change very greatly at higher current densities has an important bearing upon the distribution of the current carried by a number of brushes in parallel. The lower the current density, the steeper is the curve and the greater the tendency of the current to divide equally between all the brushes. The greater the current density, the less the drop increases with the current and the more the distribution is influenced by other conditions such as the pressure on the brushes and their temperature. While the current-carrying capacity of a brush should logically depend upon the cooling conditions and the permissible temperature rise, it will generally be found that the designer must fix upon the number of his brushes so as to keep down the current density to a value that will give sufficient stability.

Defects in brush gear.

Carbon brushes are used almost universally on commutating machines, so that the brush gear that we have to consider is a gear designed to hold a carbon brush. As carbon is a hard, unyielding material, the problem of keeping its surface in close contact with a commutator is very much more difficult than when brushes of soft pliable material such as gauze are used. Even if the commutator were perfectly cylindrical and free from eccentricity, there would still be some difficulties in the problem. As it is, we must design the brush gear so that it will work well notwithstanding slight :centricities of the commutator and slight departures from the ylindrical form.

Two general methods of holding the carbon are in use: (1) liding holders; (2) pivoted holders. In the sliding holder the arbon is allowed to slide in a box or other support, so that it may ollow irregularities of the commutator and make a good contact otwithstanding the wear that will inevitably take place. In the ivoted holder the carbon is gripped by a metal clamp, and the vhole holder is free to move about a pivot. The brush-holder that ıas found the most general favour with manufacturers to-day is he sliding holder, because it is discovered that the pivoted holder, ven when constructed so as to have a parallel motion, does not allow he brush to bed itself as truly to the commutator surface as when he carbon is permitted to slide in only one direction upon a very igid surface. Sliding holders, however, are by no means free from lefects, and there is still a good deal of room for improvement. The ideal holder would be one in which the carbon brush would be pressed against an absolutely rigid surface almost at right angles

to the face of the commutator, and while being held so that it could not move except in a direction parallel to that surface, it should be pressed towards the commutator by a pressure not too heavy and yet amply sufficient to make it follow rapidly the unevennesses of the commutator surface. While most brush gears aim at these ideal conditions, they fall short of them in the following particulars. In the box-type holder the brush is surrounded by a box which, under ideal conditions, should fit the brush exactly and yet allow it to slide perfectly freely. Such a condition is, of course, unattainable in practice, because brushes expand with heat, and would soon become too tight in a box holder that fitted them exactly. If, on the other hand, they are a loose fit in the box, a chattering action is set up in which the brush rattles from one side of the box to the other and does not present a constant facet to the commutator surface.

Side-spring holder. To meet this difficulty various devices have been employed. One of the simplest and most effective is to provide a rigid surface against which the brush slides as shown at AA' in Fig. 273, and a movable metal surface BB' on the opposite side of the carbon which presses it against the surface AA', the pressure being controlled by a spring. In this case the direction of rotation of the commutator should of course be from B towards A. In order that this type of brush-holder may be satisfactory, the following conditions must be observed: The distance from the toe of the brush t to l, the lowest point of AA', must be fairly small, say not more than $\frac{1}{16}''$, so that any frictional force between the brush and the commutator which comes into action tending to tilt the brush shall only have a very small leverage about the point l. The line ff', which gives the line of the centre of action of the force pressing the brush against the surface AA', should cut the surface AA' at a considerable distance above l, so that the ratio of $\frac{f'l}{lt}$ is fairly great, say not less than 10. Under these conditions it will be found that the force ff' can be made small as compared with the force FF' which feeds the brush on to the commutator. An example will make this clear. Let the feeding force FF' be equal to 2 lbs.; then taking the coefficient of friction even as high as 0·5, the force of the commutator upon the brush tending to tilt it will not be greater than 1 lb. (unless, of course, there are high bars, in which case it

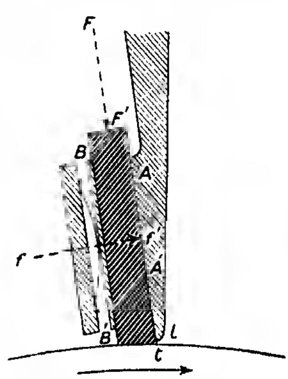


FIG. 273.—Side-spring brush-holder.

may be any amount). Assuming that the legitimate frictional forces at t cannot exceed 1 lb., and that the ratio $\frac{f'l}{lt}=10$, then any force greater than 0·1 lb. along the line ff' is sufficiently great to prevent tilting of the brush. In practice, one would make the force equal to about 0·5 lb. If now the coefficient of friction between the brush and the sliding surfaces is as high as 0·5, the total force required to overcome the friction against the surface AA' and the surface BB' will only be 0·25 lb. at each side, or 0·5 lb. total. Deducting this from the feeding force of 2 lbs., we have a residual feeding force of 1·5 lb., while the force required to push the brush up against the feeding force is 2·5 lbs. The slight friction required to move the brush in the holder is of considerable value in preventing chattering, but the conditions must, of course, be such that the frictional force never becomes nearly equal to the feeding force FF'. While a brush can be shown to work well under the conditions stated above, it is easy to understand that if these conditions are departed from the proportions between the various forces may be completely upset. For instance, if the ratio $f'l$ to lt is only 4, and there are slight roughnesses on the commutator which make the circumferential forces at t rather great, say equal to 2 lbs., it may be found necessary to so far increase the force ff' to prevent tilting action that the friction against the surfaces AA' and BB' is too great as compared with the feeding force FF'. One cause of trouble that has been found with holders of this kind is due to the fact that graphite will sometimes rub off a brush and grow on to a metal surface, forming a small wart-like growth, which is possibly aided by the passage of current from the brush to the holder. A growth of this kind fitting into a little hollow in the brush very effectually prevents the force FF' from feeding the brush forward. It has been found that if we paint the face of a graphitic brush with gum arabic dissolved in water and allow it to dry perfectly before being put into the holder, it prevents the graphite from rubbing off the brush and on to the holder. Another source of trouble in this holder is that dust and grit can sometimes get in between the brush and the surfaces A and B and prevent the proper feeding of the brush. Sometimes the station attendant will use paraffin wax as a lubricant on the commutator. Paraffin wax may soak up into the brushes and be there in such a quantity as to stick the brush to the surfaces AA' and BB' when they are cold, so that on starting up the machine the brushes spark badly because they are not being fed.

Combined feeding and steadying pressure.

Another method of meeting the difficulty found in the sliding type of holder is illustrated in Fig. 274. The surface against which

the brush slides is made extremely rigid. The top of the brush, instead of being at right angles to the face, is bevelled off so that the feeding force FF' has a considerable component at right angles to the sliding surface. Another method is to give the brush in the holder a permanent tilt by making the feeding force FF' pass

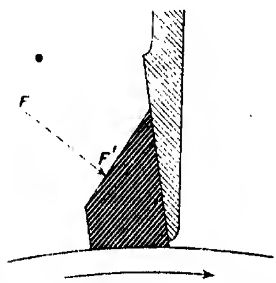


FIG. 274.—Combined feeding and steadying force.

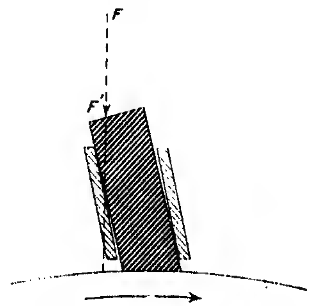


FIG. 275.—Combined feeding and tilting force.

through a point beyond the base of the brush, as in Fig. 275. In this case the brush is held by the holder only at the upper back edge and the lower forward edge, and can only rattle in the holder if the forces tending to make it rattle are greater than the component of FF' that gives the permanent tilt to the brush. The inclination of the brush should not be more than 15 degrees from the vertical when the commutator is run in the direction shown in Figs. 273, 274 and 275.

Inclination of the brush to the commutator. This leads us to consider the much argued question, What is the proper angle for the brush to make with the commutator? The answer to this question has so far never been satisfactorily given. Many engineers of wide experience will assert that in their opinion a brush works best when it is inclined " against " the rotation, while others just as positively assert that in their opinion the brushes work best when the inclination is with the rotation. Not only do some brush-holders work better one way and some better the other way, but even with the same type of holder and the same type of brush, difference of opinion will exist as to the best way of tilting the brush. The matter is very difficult to settle, because if a test is arranged it is almost impossible to reproduce the conditions sufficiently well to make the test conclusive.

The sweet running of a brush when inclined at any particular angle is dependent upon a large variety of circumstances, including the following: (1) The amount of the feeding force; (2) the component of the feeding force that tends to tilt the brush; (3) whether the tilting force upon the brush is in the direction of rotation; (4)

whether the length of the holder is greater than the working face of the brush or less than the working face; (5) whether the brush is tight or loose in the holder; (6) the angle of inclination; (7) the direction of rotation with respect to the inclination. It is obviously impossible to specify the best angle when the type of brush-holder and conditions of brush support are not specified. Indeed, it is very difficult to say in many cases exactly what is meant by "angle of inclination."

If a brush slides freely in a box-holder that is long as compared with the width of the brush, and if all reactive forces exerted on the brush by the sides of the holder are at right angles to the direction of sliding, then the resultant of all the forces of the spring and holder are in the direction of sliding, and this may be properly taken as the inclination of the brush. Suppose, however, that we have a

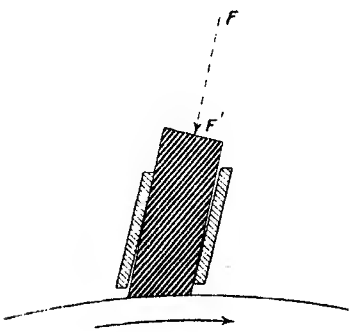


Fig. 276.

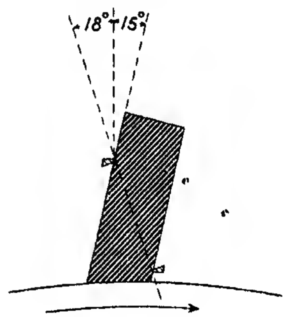


Fig. 277.

Showing the uncertainty of inclination of a brush.

brush running under the conditions illustrated in Fig. 276 and tilted in its holder so that it comes into contact with the upper and lower edges as shown. As it is only in contact with the holder along those two edges, we can imagine the rest of the box completely cut away, as in Fig. 277 (assuming, of course, that we still preserve the rigidity of the parts). To arrive at the effective angle of inclination, we must find the direction of the resultant of the force of the spring and the reactive forces applied by the sides of the holder. The direction of this resultant is often very different from the apparent angle of inclination.

Brushes inclined against the direction of rotation. A great deal of success has been obtained with brushes tilted as shown in Fig. 278. The secret of success is in making the angle of inclination so great that the brush is always slipping on the commutator and keeping itself close up against the point of the brush-holder as shown, notwithstanding the fact that the commutator surface is

moving against it. Let the resultant force FF' in Fig. 278 (which is made up of the force of the feeding spring and all reactive pressures exerted by the holder) make an angle θ with the line normal to the surface of the commutator. Then $\tan \theta$ should be considerably greater than the maximum value of μ, the coefficient of friction between the brush and the commutator. The commutator sometimes has small irregularities on it, which cause greater tangential forces on the brush than would be expected from the measured coefficient of friction; these tangential forces will disturb the pressure of the brush against the point of the holder unless the angle θ be made great enough. For a commutator in first-class condition an angle of 25° will be found sufficient; but an angle of 35° is safer for a commutator that is slightly rough. There is an objection to making the angle much greater than this, because the brush becomes so pointed that there is a danger of pieces chipping off. With brush-holders of this type the design of the feeding spring is important. It should be arranged so that it presses in the direction $F''F'$, or at any rate in a line on that side of the line FF'. If the resultant force is on the other side of FF', the effect may interfere with the correct tilt of the brush in the holder.

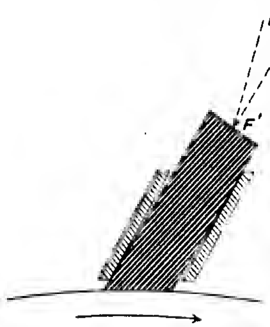


Fig. 278.—"Leading" brush inclined against the direction of rotation.

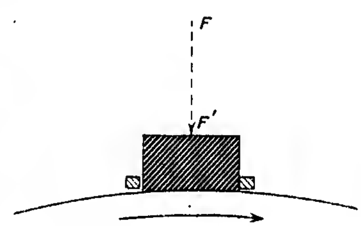


Fig. 279.—Brush with wide face and small height

Wide face and small height method. Another method of getting over the difficulty of the loose box is to make the brush with a fairly wide face and very small height, as shown in Fig. 279. If then the feeding force FF' is applied in the line almost at right angles to the surface of the commutator, it is only necessary to let the brush rest against the bar to give it a perfectly definite position. The force FF' now serves not only to feed but also to prevent either the toe or heel of the brush from lifting off the commutator. This method has been very successfully employed on D.C. turbo generators, and can be recommended in all cases where a wide brush can be employed. It has the further advantage that the brush may be made

extremely light, so that it does not require as great a force to make it follow the eccentricities of the commutator as if it were of much greater height. Sometimes a very light spring is placed between the top of the carbon and the feeding arm to keep down the mass of the quickly moving parts.

There has been in the past a very great deal of loose thinking on the problems connected with brush support; and until more precise definitions are stated and our knowledge of the conditions that affect the chattering or non-chattering of brushes is extended by systematic experiment, we shall not progress very much further in the matter.

All that we can do here is to lay down a few **general rules for guidance** in the adjustment of brush-holders. (1) See that the surface of the commutator is as perfect as it can be made, as to which see pp. 297 and 301. (2) If the brush-holder is of the side-spring type, see that the conditions set out on page 309 are observed. (3) If the brush slides in a box-holder, see that it is a reasonably good fit but not too tight. As burnt carbon brushes do not expand much with heat, it is possible to make them a fair sliding fit. Morganite brushes, however, must always be made slack in the holder, or they may become too tight when they expand with heat. (4) Assume that the angle of inclination of the brush-holder that the manufacturer has chosen is the best angle for that type of holder. When the machine is running, try to ascertain in what direction the brush is intended to tilt in the holder if it tilts at all; that is to say, whether you have the condition shown in Fig. 276 or the condition shown in Fig. 278. Having made up your mind as to which way you intend the brush to tilt, see that all the conditions as to the application of feeding force and the frictional forces are such as to preserve the tilt in question. (5) See that the feeding force on each brush is sufficient to make it feed rapidly and follow any eccentricity of the commutator.

Chattering.

The word "chattering" is used to denote two different kinds of motion of a brush. A brush may chatter by moving in the plane in which it is supposed to slide: for instance, by moving in a line parallel to the plane *AA′* in Fig. 273. This may be spoken of as vertical chattering. Or it may chatter by vibrating in a line parallel to the face of the commutator. This we will call tangential chattering. Sometimes the two kinds of chattering occur together, and the occurrence of one may be the cause of the other. All the causes of chattering are by no means understood, nor has any thorough investigation as yet been made upon this important subject. Some of the causes of chattering are the following:

Vertical chattering. If a brush slides very freely in its holder and is lifted a short distance from the commutator and then allowed to drop under the force of the feeding spring, it will tend to bounce, the height of each bounce being a fraction of the height of the last bounce. The greater the friction in sliding, the smaller will be this fraction. If the friction resistance to sliding is half as great as the feeding force, the amount of bounce will be a very small fraction of the height from which the brush has fallen. If now there is some unevenness on the surface of the commutator, which is moving under the brush at a great velocity, a continual bouncing of the brush will occur, because upon the whole there will be a tendency, when the brush is on the downstroke, for it to hit on the front side of a protuberance rather than on the back side of the protuberance. If it hits upon the front side of the protuberance, then there is a force upon it tending to throw it upwards, so that if the brush can move very freely in its holder and has a tendency to bounce (the energy of the bounce not being absorbed in a single stroke), the striking of a brush against the front side of protuberances will convey enough energy to keep the brush continually bouncing—that is to say, to keep it chattering vertically.

There seems to be some evidence that when a commutator is hot chattering of this kind is very much aggravated; and one is tempted to believe that some of the energy communicated to the brush on each stroke may be due to the expansion of the carbon when it strikes the hot copper, the action being similar to the curious phenomenon known as the Trevelyan rocker. This matter, however, needs further investigation. Whether the action is due to expansion or not, it is perfectly well established that we may have very bad vertical chattering of brushes even when the commutator is highly polished and free from high bars or uneven surface.

Tangential chattering. Wherever there is a looseness of the brush-holder and no regular force tending to make it tilt in one definite direction in the holder, chattering is likely to occur. This is because the friction between the brush and the commutator drives the brush forward in the holder with some velocity until it strikes against the side of the holder. It then rebounds to the other limit of its motion in a tangential direction, comes in contact with the commutator again, and so the action is repeated. Tangential chattering set up in this way may bring about vertical chattering, because the striking of the brush against one or other of the sides of the holder generally introduces a force having a vertical component sufficient either to lift the brush off the commutator or to drive it on to the commutator with such force that it rebounds. Under these conditions, the point on a brush may move in a more or less elliptical orbit, the energy required for the motion being

supplied by the frictional forces exerted by the commutator; and the action may be aggravated by unevenness in the commutator.

Another kind of tangential chattering, which may occur even when the brush is perfectly tight in the holder, is due to the springing of the holder or its supports. If we have a brush-holder supported by an arm as shown in Fig. 280 and the position of the support of the arm is such that any tangential pressure upon the brush-holder in the direction of rotation tends to spring the brush support in an arc of a circle, as shown in the figure, so that the further it springs the greater is the pressure between the brush and commutator, we have a condition that permits of very bad chattering. The frictional force of the commutator upon the brush pushes the holder forward until it is balanced by the resilience of the brush-holder support. If now the friction is minimised by any cause, say the sudden yielding of the brush in its slide, the holder will spring back

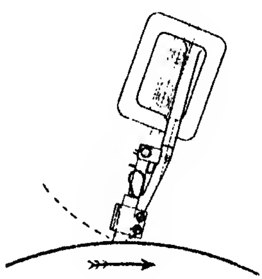


Fig. 280.

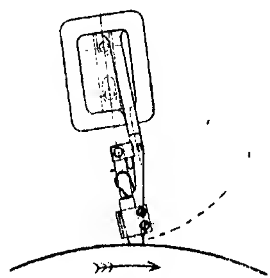


Fig. 281.

to its original position, the brush then springs out again, the friction again bends the brush arm, and so the action is repeated. Supports of the brush-holders should always be designed so that when any yielding of the brush support in a tangential direction occurs, the arc of the circle along which it moves is as shown in Fig. 281 —that is to say, the frictional forces are diminished rather than increased by such tangential motion.

Heating due to chattering. Chattering produces heating of the commutator and brushes on account of increase of friction losses and increase of resistance to the passage of current. However much a brush may bounce upon the commutator, the mean pressure between brush and commutator is not less than the pressure exerted by the feeding spring, so that the friction on the surface of the commutator is at least as great when chattering as when the brush is running smoothly. In addition to this, we have the energy lost in the impact of the brushes and friction losses in the brushes sliding

in the holders. Experience shows that when bad chattering occurs, the friction losses may be increased twofold. Resistance losses may be increased manifold when there exists a short arc under the brushes instead of a close electrical contact.

Cure for chattering. The best cure for chattering is to find out the cause, which may be one of those enumerated above, and to remove it. The chattering due to a hot commutator is sometimes difficult, if not impossible, to get rid of. Lubrication of the surface of the commutator with paraffin wax is sometimes resorted to; but it may require too much attention if the commutator has to be lubricated every hour or two. If the brushes are boiled in paraffin wax and thoroughly saturated, the wax will be slowly fed to the contact surface, and sometimes lasts for several months. The wax lasts longest when the brushes run cool. If the brushes are very hot, the paraffin is fed to the contact surface quickly and soon disappears. Sometimes a change of the grade of brush is of assistance: a brush having a large amount of graphite in its composition runs more smoothly than a harder brush; but even brushes of pure graphite will chatter when the conditions are bad. The introduction of a little friction into the sliding of the brush is helpful. Care must be taken that this friction is not so great as to stop the quick feeding of the brush when the commutator runs slightly eccentrically. The changing of the tension of the feeding springs sometimes has a marked effect upon chattering. It may be that the cause of chattering is synchronous with the natural period of vibration of the brush in its holder, and anything that changes the period of vibration of the brush may reduce the chattering. Tangential chattering due to any of the causes mentioned above can be cured by removing the cause; but vertical chattering is not yet sufficiently understood, and with some brush-holders it may defy all attempts to cure it. The best plan in these cases is to change the brush-holders (see page 308).

It has been noticed that where the mica has been cut out of the commutator chattering occurs more freely than where the mica is flush with the commutator surface. As the cutting out of the mica does not of itself produce any protuberance that should aggravate chattering, it may be that the reason is to be found in the fact that with a smooth commutator and well-fitting brush the motion of the brush is damped by the air, a little force being required to quickly lift off a well-fitting wide brush against the pressure of the air. If, however, grooves are cut in the commutator, these may feed the air under the brush and enable it to rise more freely. It is possible that one of the main actions of a lubricant in stopping chattering is in the adhesion that it gives between the surface of the brush and the surface of the commutator.

Failure to feed.

It not uncommonly happens with box type and other holders that the carbon sticks and the spring is not sufficient to make it feed. In all cases of sparking at the brushes this should be looked to at once, as it is perhaps the commonest cause of trouble. A good plan is to lift each brush by its pigtail and see whether it snaps back on to the commutator when released. If it does not do so, it should be taken out and cleaned, the brush-holder should be blown out, and any other adjustments made that are necessary to bring about a nice snappy feed when the pigtail is released. At the same time care should be taken that nothing is done to make the brush *too* loose in the holder.

Too great pressure between the brushes and the commutator.

Sometimes on account of the bad feeding of the brushes the feeding springs have been screwed down until the pressure between the commutator and the brushes is too great. Any friction between the brush and the holder increases the pressure, when owing to a slight eccentricity of the commutator the brush is in the act of being lifted. When the brush is falling, the frictional force is of course subtracted from the feeding force. Excessive pressure may bring about heating of the commutator and reduce the efficiency of the machine. Where a brush-holder is well designed and in good condition, a pressure of $1\frac{1}{2}$ lb. to the square inch is quite sufficient to maintain good contact up to speeds of 5000 feet per minute.

Pigtails or shunts.

All brushes of the sliding type should be provided with a flexible copper conductor for conveying the current from the brush to the holder. It is better that these shunts or pigtails should be of too great cross-section than too small cross-section. The current is very seldom evenly distributed between all the brushes, so the pigtail should be designed to take a very heavy overload without overheating. The pigtail should be bent into a form that permits of great flexibility. Sometimes a brush will not feed because the pigtail has been bent into such a form that part of it is acting as a strut and part of it as a tie-rod interfering with the motion of the feeding spring.

It is important that the electrical contact between the pigtail and the brush shall be of very low resistance. Sometimes the contact will become defective and the current is then thrown on to other brushes which thus become overloaded.

Brush-holder supports.

In a paragraph above, some matters relating to the position of the brush-holder supports were pointed out. In addition to these,

we would say that rigidity is of the greatest importance in a brush-holder support. The method of insulating the support should be such that when the insulation shrinks, as it very often does, it does not enable the support to alter its position. A great deal of time and money has been wasted in the past owing to neglect of this particular. Much care may be taken with the spacing of the brush-holders and in bringing about good commutation, and yet after a few months the whole of the work has to be done over again, because the brush-holder supports have shifted.

Brushes badly ground in.

If the faces of the brushes do not exactly fit the face of the commutator, the current-density may be excessive and the commutating period too short to permit of good commutation. When grinding in brushes, the direction in which the emery-cloth or sand-paper should be drawn while the brushes are pressed upon it depends upon the inclination of the brush to the direction of rotation. Where the brushes are inclined "with" the direction of rotation, as in Fig. 275, the grinding should be done in the same direction as the normal movement of the commutator. But where the brushes are inclined "against" the direction of rotation, as in Fig. 278, the grinding should be done in a direction opposite to the normal rotation of the commutator.

Rocker-ring.

The rocker-ring to which the brush-holder supports are attached should be capable of being locked so that not only are the brush-holders fixed against motion in a circumferential direction but are free from the shake that sometimes arises from looseness of the rocker-ring. The movement of a rocker-ring in its support sometimes brings about sparking, the cause of which is not at once apparent. The brushes may be perfectly ground in and adjusted most perfectly with the rocker-ring in one position. Owing to vibration or some other cause, the rocker-ring moves slightly and the bedding of the brushes is spoilt.

Skewed brush-arms.

Sometimes the line of the brush-holders is not parallel to the axis of the shaft and as a result the commutator bars pass some of the brushes before others. The effect of skewing the brush-arms in a symmetrical manner is virtually to widen the zone of commutation. If it is done in an unsymmetrical manner it brings about unequal loading of the brush-arms.

CHAPTER X

SPARKING AT THE BRUSHES (*Continued*)

COMMUTATION.

UNDER this heading we will consider all matters relating to the change of the direction of the current in the coils as they pass the brushes and in the distribution of current between the various brush arms.

Every engineer who essays to find the reasons for defects in commutation should make himself thoroughly acquainted with the theory underlying commutation and with the laws controlling the distribution of potential on the commutator (see page 282). Commutation in its simplest conception can be studied by means of a

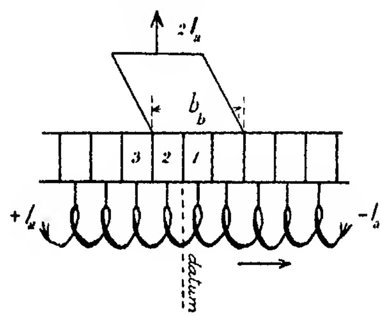


FIG. 282.

small model made after the manner of Fig. 282 in which the commutator bars and connected winding are drawn on a slip of cardboard which can be placed above a piece of paper on which the brush is drawn. By sliding the cardboard commutator past the brush we imitate the process which occurs on the commutator and can fix our ideas as to the position of any coil and the value of the current in that coil. We may, for instance, take as our index mark of position the mica between commutator bars No. 1 and 2, and fix

our attention upon the coil which connects bars 1 and 2. We will suppose that the rotation of the commutator is from left to right. The brush in Fig. 282 is delivering the current $2I_a$ to the outside circuit. Move the coil 1, 2 well to the left of the brush. Then it is clear that if bars 1 and 2 are not in contact with the brush, the current I_a (= half the current collected by the brush), will be flowing through the coil from left to right on its way to the brush. If we move the coil in question well to the right so that bars 1 and 2 are past the brush, then the current in coil 1, 2 must be flowing in the opposite direction, and we may denote it by $-I_a$. It is clear, therefore, that as the coil 1, 2 passes the brush the current must change from $+I_a$ to $-I_a$. We may make a diagram which shows the value of the current of the coil in question for various positions of the index mark 1, 2. Such a diagram is given in Fig. 283. The current

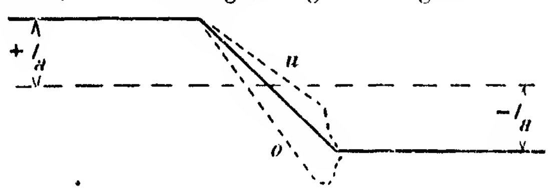


FIG. 283.

keeps constant at the value $+I_a$ until the index mark reaches the edge of the brush, when it may begin to fall. It then passes through zero and changes gradually to the value $-I_a$ before the index mark passes away from the toe of the brush. If the current follows the law shown by the full line in Fig. 283, we have what is sometimes called "straight-line" commutation, the rate of change of current in the coil being uniform and of exactly the right value to enable the current $-I_a$ to be reached at the right instant. The self-induction of the coil opposes the change of current in the coil, so that if no commutating E.M.F.'s were operating the current would only sink slowly, and it would not be until the index mark had nearly reached the toe of the brush that the resistance of the brush would compel the current to change quickly to the value $-I_a$. This state of affairs is sometimes spoken of as under-commutation, and is shown by the dotted line marked *u* in Fig. 283. If there is a strong commutating E.M.F. tending to change the value of the current in the coil very quickly, it may make the rate of change of the current too great, so that it sinks very quickly from the value $+I_a$, becomes negative early in the commutating period, and reaches the minus value greater than $-I_a$, in which case the resistance of the carbon brush must in the last stages of commutation force it down to the value $-I_a$ before the index mark passes the toe of the brush. This state of affairs is spoken of as over-commutation, and is shown by

the dotted line in Fig. 283 marked *o*. The problem of the engineer who is adjusting the commutation of the machine is to arrange matters so that during the commutation interval in which the index mark passes from the heel to the toe of the brush the current will change at just such a rate in the short-circuited coil as to reach the value $-I_a$ exactly at the instant when the index mark passes from the toe of the brush. It is not, of course, necessary to always have straight-line commutation. Some designers arrange the field-form of the commutating pole so as to give a law of change like that indicated in Fig. 284. The advantage of this arrangement is

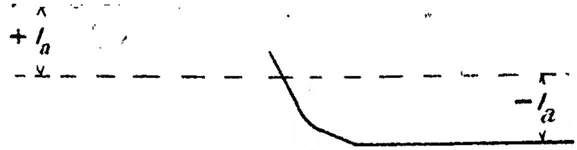


FIG. 284.

that the rate of change of current, though very great when the index mark is in the centre of the brush, is not so great as the index mark nears the toe of the brush. Any little want of adjustment of the commutating pole is more readily corrected by the resistance of the brush when the slope of the curve is small than when the slope of the current curve is steep. The slope of the current curve being steep in the middle of the brush does not matter, because trouble is not ordinarily experienced in the middle of the brush.

Before the introduction of commutating poles the ordinary practice was to rock forward the brushes on a generator so that the coil under commutation was subjected to an E.M.F. tending to reverse the current, and if this E.M.F. was exactly the right strength the commutation curve was fairly straight. The E.M.F. necessary to overcome the self-induction of the winding of course depends upon the rate of change of the current in the winding. The commutation interval t_c is fixed when the width of the brush is fixed. If the rate of change of current were constant it would be $\frac{2I_a}{t_c}$. This multiplied by L, the coefficient of self-induction of the coil, gives us the E.M.F. necessary to bring about straight-line commutation. If we widen the brush we lengthen the commutation interval and reduce the value of the required commutating E.M.F. As the load increases from zero up to its full-load value, the value of the commutating E.M.F. should be increased in proportion. It is clear, therefore that the plan of rocking the brushes forward to a point which gave approximately straight-line commutation at full load was not satisfactory, because the commutating field was too strong for light loads

and too weak for over-loads. The modern plan of providing a commutating pole whose strength varies in proportion to the load is very much more satisfactory. Moreover, it enables the brush to be placed on the mechanical neutral (see page 279), and avoids the demagnetizing effect which is produced on the generator when the brushes are rocked forward. It is not our purpose here to go fully into the design of commutating poles. It is sufficient to point out a few features which are of interest to the engineer who may have to adjust them.

In a generator the commutating pole should be of the same polarity as the next succeeding main pole. That is to say, that if the coil under commutation is passing from a south main pole to a north main pole on a generator the commutating pole should be a north pole. If it is passing from a north main pole to a south

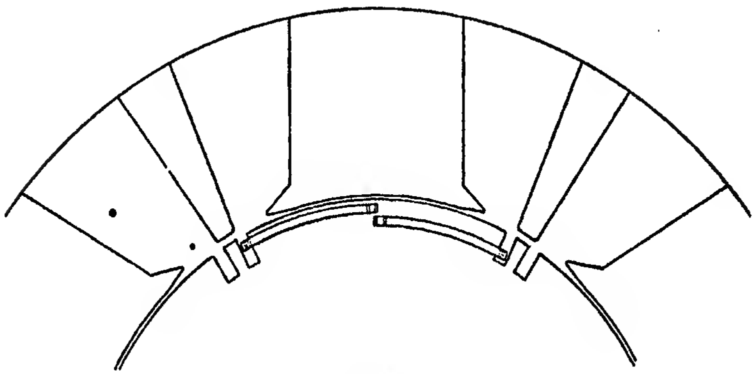


Fig. 285.

main pole the commutating pole should be a south pole. The width of a commutating pole shoe should be sufficiently great to subject all the conductors lying in one slot to the commutating flux while the coils are under commutation. If we are dealing with a full pitch coil, both sides of the coil will have the same phase position with regard to the commutating pole, but, if as is more commonly the case, the coil has a short throw the two coil-sides will have a different phase position, as shown in Fig. 285, in which case one coil-side passes under the middle of the commutating pole before the other. This has virtually the effect of widening the zone of action of a narrow commutating pole. It is, in fact, sufficient in such cases to give to the commutating pole a width of only one-half of the commutating zone, because if the field strength is twice as great as it need be on a wide pole we can have twice the commutating E.M.F. set up in one of the coil-sides for one-half of the period and twice

the commutating E.M.F. set up in the other coil-side for the remainder of the period, instead of having a normal commutating E.M.F. in both of the coil-sides for the whole period. The short-throw coil with the narrow commutating pole is also convenient for giving to the commutation curve the shape depicted in Fig. 284, because we get virtually superimposed two commutating field-forms *A* and *B* in Fig. 286, the sum of which is equal to the field-form *C* where the throw of the coils and the width of the commutating poles is such as to make their effects overlap. Thus we get a much greater commutating E.M.F. in the middle of the commutating period than at the end of the period. Some machines are only provided with one commutating pole for every pair of main poles, this one commutating pole being made sufficiently strong to generate enough E.M.F. in the two half coils which pass under it.

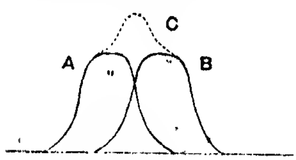


FIG. 286.

As a rule the air-gap under a commutating pole is made fairly great, say from ·25″ to ·75″. The reason for this is that it is desirable to make the field strength proportional to the load, and as the permeability of iron is very far from constant it is best to make the reluctance of the iron part of the circuit small as compared with the reluctance of the air-gap. Sometimes the pole shoe of a commutating pole is shielded with copper or surrounded by a highly conducting electric circuit for the purpose of keeping the flux from changing its position when the teeth of the armature pass under it (see page 353). The thick copper shield opposes any sudden changes in the shape of the field-form, and in that way makes the E.M.F. in each conductor in the slot follow more exactly the law intended for it, freed from the effect of tooth ripples which are set up by the passage of the highly magnetized iron teeth under the commutating pole.

Notwithstanding the provision of a large air-gap under the commutating pole, the reluctance of the iron of the magnetic circuit cannot be entirely neglected, and at heavy loads the reluctance of the magnetic circuit is far from being constant. For this reason a commutating pole which has been adjusted to be exactly right on full load is often found to be too weak on 50 per cent. over-load because, owing to the saturation of the iron of the magnetic circuit, the number of ampere-turns required to give the right field strength are more than 50 per cent. greater than the ampere-turns required at full load. The saturation of the iron of a commutating pole is aggravated by the very large number of turns which must be put upon the pole in order to neutralize the armature ampere-turns. If we

refer to Fig. 233, we see that the magneto-motive force of the armature of a generator tends to magnetize the iron of a commutating pole in the opposite sense to that required. That is to say, that it tends to make the commutating pole *CP* in Fig. 233 into a north pole, whereas we wish it to be a south pole on a generator. It is necessary therefore that the series winding on it should carry enough ampere-turns to more than overcome the armature ampere-turns and to give it a south polarity of sufficient strength to bring about commutation. On the machine a diagram of whose field-form is given in Fig. 233 the ampere-turns on the armature amount to 8000 per pole. The length of the air-gap on to the commutating pole is 1 centimetre and the flux density 4440, so that the resultant ampere-turns required are about 4000. These must be added to the 8000 turns of the armature, giving a total of 12,000 ampere-turns required on the commutating pole at full load. The very large magneto-motive force exerted by these ampere-turns produces very heavy magnetic leakage.* A fairly large cross-section of iron is necessary, especially at the root of the commutating pole, to provide a path for the leakage and working flux without saturating the iron. Even when ample cross-section of iron has been provided for full-load conditions, the leakage occurring on 50 per cent. overload may be so heavy as to partly saturate the iron and call for many more ampere-turns than are provided at 50 per cent. overload in order to yield the correct commutating flux.

Correcting effect of carbon brushes.

It will be seen from what has been said above that under practical conditions it is impossible to adjust a commutating pole so as to make the field strength of exactly the right value for all loads. All that can be done is to generate a commutating E.M.F. which shall approximately do the work of reversing the current in the coils under commutation during the commutating interval. One must trust to the resistance of the carbon brushes to finally bring the reversed current to the correct value before the index mark leaves the toe of the brush. The carbon brush is very effective in bringing about this correction. Theoretically, the current from bar No. 1, Fig. 282, should reach zero value when the index mark reaches the toe of the brush. If there is any current flowing from bar No. 1 to the brush an instant before the index mark reaches the toe, it will create a very high current density at the point of contact by reason of the fact that the area of the brush touching bar 1 is rapidly approaching zero. If there is a finite current from bar 1 at the time when the area approaches zero, the current density becomes exceedingly great and the voltage drop very considerable.

* See page 348 as to method of reducing the leakage.

If we look at the curve of brush drop given in Fig. 258, we see that the voltage rise for very heavy current densities does not rise in proportion to the current density. It, in fact, tends to become constant, the constant depending upon the character of the brush surface and the length of the short arc which exists between the carbon and the copper. Experience shows that a brush drop of from 3 to 5 volts can exist under the toe of a brush before it shows appreciable sparking. It appears that when the commutating E.M.F. is not properly adjusted, so that the current density under the toe of a brush becomes excessive, the carbon is burnt away so that it does not touch the copper, the length of the arc under the toe probably not being more than ·0001″. This short arc, however, is sufficient to give the requisite back pressure to force the current in bar (2) up to the proper value before the index mark leaves the toe of the brush. It is not well, however, to call on the carbon brush to exert a back pressure of more than 2 volts as a correcting influence. If we fix on this figure of 2 volts, we are able to see by what percentage the adjustment of the commutating pole may differ from its proper value before the 2 volts is exceeded.

In the 1000 K.W., 500-volt, D.C. generator, particulars of whose field-form are given in Fig. 233, the E.M.F. required to be generated in one coil in order to bring about proper commutation at full load is 3 volts. As there are 4 coils short-circuited under the brush, the total voltage to be generated in these 4 coils is 12 volts. If through defective adjustment of the commutating pole the total voltage in the 4 coils is only 10 volts, we can rely upon the back pressure exerted by the toe of the carbon brush to force the current in the last bar to reach its correct value before the index mark leaves the toe of the brush. Or if the commutating pole were adjusted to such a value as to generate 14 volts (2 volts more than the required figure), we might again rely upon the carbon brush to exercise its correcting influence. We see, therefore, that an error of 15 per cent. in the adjustment of the commutating pole does not bring about any serious sparking. The sum of all the E.M.F.'s generated by the commutating pole in all the coils under commutation at one time is sometimes spoken of as the "voltage under the brush." This voltage does not appear on the commutator because it is absorbed by the self-induction of the armature winding (see Fig. 241). The self-induction of each armature coil is such that it requires 3 volts to overcome the self-induction when the current is changing at the rate required for commutation at full load. For convenience of expression we speak about the 3 volts being generated by the pole, but in reality the volts are not generated in the coil, the flux change created by the change in current being exactly balanced by the flux change occurring as the coil moves in the magnetic field of the pole. This is what

we mean by saying that the voltage generated by the commutating pole is absorbed by the self-induction. Nevertheless, it is of importance to consider the total volts under the brush because if it is large the commutating pole will have to be very finely adjusted in order that the total error may not exceed 2 volts. For machines of normal speed it is generally considered that a total voltage of 20 volts under the brush is a possible practical figure, because it permits of an error of 10 per cent. in the adjustment of the commutating pole without calling for more than 2 volts correcting influence of the carbon brush. Good modern machines, however, will commonly be found with voltage under the brush between 10 and 15 volts.

If it is desired to know exactly the amount of the voltage under the brush, it may be measured in the following manner. Lift all the brushes; excite the commutating pole with the number of ampere-turns equal to the resultant ampere-turns upon it at full load. By means of voltmeter points, applied as described on page 336, find the difference of potential at points immediately under the toe and heel of a brush. When the brushes are removed from the commutator the full voltage generated by the commutating pole, as shown by curve AA' in Fig. 241, appears on the commutator. It will be seen that for the case illustrated in Fig. 241, the voltage under the brush is the difference between 265·5 and 253·8—that is to say, 11·7 volts. When the brushes are down and the generator running on full load these volts are entirely neutralized by the self-induction of the armature coil, so that the potential distribution curve takes a shape like curve BB'. The potential of the brush may be about one volt lower than the horizontal part of BB' as given by the thick horizontal line.

Distribution of current between the brush arms.

One of the most important factors in securing good commutation is to see that the current is evenly distributed between the brush arms. This is a matter of importance, because the commutating poles are usually all adjusted to equal strength, and they cannot therefore be properly adjusted for each brush arm unless each brush arm is carrying the same current. In practice it is found a little difficult to make the current in all brush arms the same. In order to properly understand the factors which control the current in each brush arm, we must have a proper understanding of the commutator potential curve, such as that shown in Fig. 236. In the ideal machine, each of the waves of the potential curve is exactly similar and is exactly the same height above and below the zero line. If these conditions could be attained in practice and the brushes were spaced exactly a pole-pitch apart, all the brushes of the same polarity when placed with their centres opposite the

mechanical neutral at no-load would be at exactly the same potential and no current would tend to flow from one brush to another.

Further, under these ideal conditions we could rock all the brushes forward, and the only effect would be to lower the potential of the centre of each brush; but the potential of the centres of all the positive brushes would be equal, and the same may be said of the negative brushes. The effect of rocking the brushes forward so that they come on to the slope of the potential curve is, of course, to raise the potential of the heel of the positive brush to a point higher than the middle and to lower the potential of the toe of the brush below the potential of the middle. The effect of this is to create an eddy current under the brush, current passing in at the heel and out at the toe of the positive brushes and *vice versa* in the negative brushes. So long as the brushes are rocked forward only a little way and the slope of the part of the potential curve on which they lie is not great, this eddy current will only be small; but if the brush is rocked forward until the total voltage under the brush as represented by the difference of potential between the heel and the toe measured on a potential curve is greater than 5 volts, fairly heavy eddy currents will flow, and when the voltage under the brush is as great as 10 volts, very heavy sparking will be visible. So far our remarks have applied to the ideal machine, in which the waves of the potential curve are absolutely similar and of the same height and on which the spacing of the brushes is perfectly accurate. It is easy for the engineer who is familiar with the meaning of the potential curve to judge how far the brushes may be out of spacing or the waves of the potential curves deviate from equality before deleterious effects are noticed on the machine. If we take the potential curves drawn to scale in Fig. 239, and imagine positive and negative brushes put upon the positive and negative waves respectively, we can see that owing to the flatness of the tops of the waves the brushes may be considerably out of spacing before much current circulates between one brush and another. A current of any magnitude passing from the commutator to the brush or from the brush to the commutator will create a drop of about 1 volt. We can therefore move any of the brushes from the no-load neutral to a point on the potential curve which is nearly 2 volts lower than the highest point before any series current circulates at no-load. Thus on the machine in question a single positive brush can be rocked forward or backward by 0·6 inch before there is a potential difference of 2 volts between it and the brushes which remain on the mechanical neutral. It will be seen later that the latitude in bad spacing which is permissible at no-load is not permissible at full load, because when all brushes are collecting current, and the

normal maximum brush drop of about 1 volt is already in existence on all brushes, it is not permissible to have a difference of potential of 2 volts between the points of brush positions on the potential curve because that 2 volts would make a very great difference in the current collected by the brushes in question.

Methods of investigating the current distribution at full load. After we have satisfied ourselves that we have all the conditions necessary for the good collection of the current at the brushes, the next step is to find out how the current is distributed between the brush-arms. A rough method which works well enough in practice is to take the milli-volt drop in each brush-arm, the voltmeter points

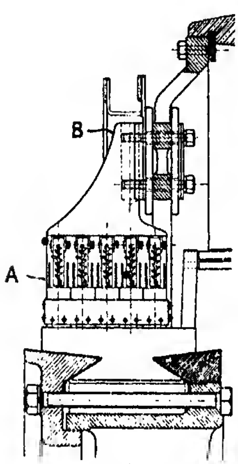


Fig. 287.

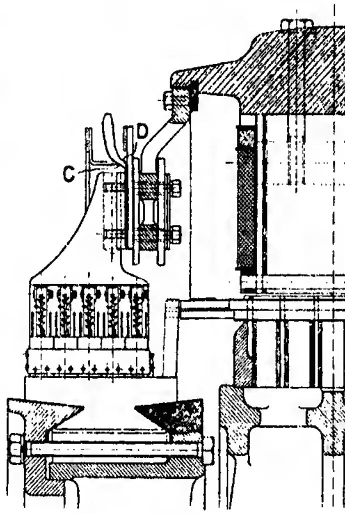


Fig. 287A.

being applied as shown in Fig. 287 at *A* and *B*. For this purpose we must scrape off paint or varnish from the brush-arm so as to get on to the bare metal, and we must be careful that the points *A* and *B* touch the metal of the arm itself and not merely the metal to which it is bolted, because the drop in the joint between the metals may be great as compared with the drop in the brush-holder arm itself and is of uncertain amount. Where brush-arms are made of cast-iron the drop, even at low loads, is usually sufficient to be measured on a milli-voltmeter, and the resistance of the brush-arms may be taken as approximately the same provided we employ the same points *A* and *B* on each one. It is not uncommon to find the brush-arm drops on machines that are operating quite well differing by very large percentages. Sometimes the current taken by one brush-arm may be double the current taken by another, and

yet the sparking is not appreciable. This goes to show how very effective the carbon brush is in correcting the work of the commutating pole. For, obviously, the commutating pole, if adjusted to the right value for one of the brush-arms, must be very much out of adjustment for the other one. It is best to make a record of the brush-arm drops in the following way:

Chalk on each brush-arm its number, beginning, say, at the top of the machine, and going clockwise around the commutator. Odd numbers, let us say, are positive and even numbers negative. The polarity should be ascertained by means of a voltmeter the marking of whose terminals is beyond suspicion. It is well to have the handles of the voltmeter points painted red and blue, the red always being used for positive, and being connected to the positive terminal of the voltmeter. Having numbered all the brush-arms we begin, say on a positive brush-arm, putting the red voltmeter point at *A* and the blue on *B*. We should now get a positive reading. It is important to check this because it is not impossible for a so-called positive brush-arm to be actually putting down current instead of picking it up through some dissymmetry in the machine. Now go round all the positive brush-arms, always putting the red to *A* and blue to *B*, and write down in a notebook the number of and the corresponding drop in the brush-arm, noting, of course, that they are all positive. Now go round all the negative brush-arms in the same way, putting the red point on *B* and the blue point on *A*, and note that all brush-holders of even number are negative. If all the drops are within 10 per cent. when the machine is on full load, the adjustment in this respect is quite as good as one finds in practice, and it may not be worth while to try to improve the current distribution unless the conditions of commutation are very severe, so that good commutation could only be expected with the very finest adjustment. As a rule it is found that the differences of the brush drop in the various arms are very much more than 10 per cent. In experimental tests, where some precision may be necessary, it is not sufficient to assume that the resistance of the brush-arms is the same, and it may be necessary to connect resistances in series with them. A convenient method of putting in a resistance is to fold over a strip of German silver, as shown in Fig. 287 A, place a piece of fuller board between the two flat ends, and bolt this between the brush-holder arm and its support so that one end of the German silver strip is in contact with the brush-holder and the other in contact with the metal which normally collects the current from it. We may now attach our milli-voltmeter points at *C* and *D*, and the milli-voltmeter readings then give a positive indication as to the current distribution, because we can give to all our German silver resistances the same value.

Adjustment of current distribution. Where it is established that the current distribution between brush-arms is not uniform, the next step should be to check very carefully the **spacing of the brush-arms.** Many methods have been proposed for the accurate spacing of brush-arms, some of which have proved to be rather difficult to carry out in practice. Some engineers, for instance, wrap a strip of paper round the commutator, thus finding the exact circumference. This circumference is then divided into as many parts as there are brush-arms, and evenly spaced lines are ruled on the paper, which is again wrapped around the commutator so that the lines come near the toes of the brushes. It is then seen whether the brushes toe the lines all round the commutator. On a big commutator, however, it is rather difficult to get the paper uniformly stretched, and when a commutator is hot it will be found that the paper shrinks in those parts where it is heated up by the commutator; and even if the lines were originally evenly spaced, the stretching and the shrinking of the paper may put them out of spacing. For this reason a strip of copper tape is more satisfactory than a strip of paper, and may be used where it is available.

The best method, however, is to have the brush spacing marked out on the edge of the commutator, and some makers have this done before the machine is shipped. For this purpose a groove is scratched in the radial face of the commutator at its external end, and on this groove punch-marks are made exactly evenly spaced.

FIG. 288.—Curved metal strip, with radial edge for the accurate setting of brushes.

A strip of iron having one end turned down, as shown in Fig. 288, is laid against the toes or the heels of the brushes of one of the brush-arms. It is easy to see whether the edge of the strip comes exactly opposite the centre of one of the punch-marks. The iron strip to work well should be given a curvature (shown in the figure) rather greater than that of the commutator, so that it lies in a perfectly positive position. Where a commutator is graduated, all that is necessary is to turn it until the punch-marks come opposite the toes of the brushes and then apply the steel edge. It can at once be seen whether any brush is slightly forward or slightly backward of the mean position. It is not always safe to assume that the man who spaced out the punch-marks has done them uniformly. Where any doubt exists the punch-marks should be checked with a good pair of trammels. After the trammels have been set as nearly as possible to the correct spacing, it is well in going around

the commutator not to put the point of the trammels in the punch-marks, because the sloping side of the punch-mark may automatically correct slight errors and so prevent the accumulation of errors. It is best to put one point of the trammels just outside the punch-mark, say $\frac{1}{16}''$ away from it, and with the other point describe a part of a circle on the copper, making a scratch about $\frac{1}{16}''$ from the side of the next punch-mark. Then put the first point exactly on that scratch and make a scratch near the nearest punch-mark, and so on round the commutator. After we have gone right around the commutator, if the trammels have been properly set the last scratch will coincide with the point on which we began. If this is not the case, we must reset the trammels by their screw adjustment and go around the commutator again until we find that the adjustment is exactly right. We can then check the spacing of the brush-arms exactly.

Taking the same sheet of the notebook on which we have entered the numbers of the brush-arms and the current distribution, we can now add the additional information as to the spacing of the brush-arms. On generators where the brushes have been rocked slightly forward to aid commutation, it will generally be found that those brush-arms which are collecting the smallest current are spaced so that they are slightly in advance of the mean position, and those which are taking the biggest current are slightly behind the mean position. Where this is found to be the case, the remedy obviously is to correct the spacing of the brush-arms. If the brushes are rocked backward the current distribution is sometimes very erratic, and bears no simple relation to the spacing of the brushes. Upon the whole, those brushes which are farthest back will take the least current. In machines which have their brush-arms clamped tightly to a metal face which is at right angles to the axis of the machine there will generally be found some play in the clamping bolts, so that the brush-arms can be shifted a little when the nuts are loosened. Sometimes, however, the play in the bolts is not sufficient to enable all the brush-arms to be correctly spaced. When this is so the brush-arm must be taken off and the holes eased out with a round file. Sometimes by making the mean position a little farther back or a little farther forward, we can do away with the necessity of filing out bolt holes. After the brush-arms have all been correctly spaced, the limit of error being not more than ·01″, the brushes must be ground in on those arms which have been adjusted so as to get proper contact between the brushes and the commutator over the whole of their surface. It is well to pass the emery cloth under all the brush-arms after a brush spacing so as to get all the surfaces in a similar condition. The spacing should then be checked again, and if the spacing is being checked by the punch-

marks on the edge of the commutator, it is well to try these punch-marks in two or three different positions, say with the commutator turned round through 90° and then 180°. This has the effect of checking the spacing of the punch-marks if this has not already been done. We can now run the machine on load again and check the current distribution.

Usually it is found that unequal current distribution is due to bad brush spacing, and it is cured by correct brush spacing. This is, however, not always the case. The following are some other possible causes of bad current distribution:

(1) **Uneven tension of the brushes.** If the springs of some of the brush-holders are adjusted so as to make the tension of the brushes very much greater on some brush-arms than on others, the brushes with the heaviest tension may collect more current than the brushes with the light tension. Sometimes the adjustment of the brush tension may be useful in making fine adjustments of current distribution.

(2) **The poles may be unevenly spaced.** On machines that have their poles cast in, it is not uncommon to find that through shrinkage of the yoke in cooling the whole spacing has been considerably disturbed. If this has not been corrected afterwards by chipping the edges of the pole, the potential curve will be so disturbed that the points of highest potential are not evenly spaced. When this is the case the simplest plan is to space the brushes so as to fit the potential curve. One difficulty, however, is that the irregularity in the potential curve changes from no-load to full load, and where poles are very badly spaced it may be impossible to get good commutation at all loads owing to this circumstance. When it is desired to get the best commutating conditions the spacing of the poles should be very accurately carried out. Sometimes on machines with bolted-on poles the spacing is not carried out as well as it might be. A cumulative error of $\frac{1}{16}''$ is sufficient to affect the commutation.

(3) **Unequal strength of the poles.** This may be due to uneven air-gap or to blow-holes in the yoke. Where the reluctance of those parts of the magnetic circuit represented by the air-gaps, pole bodies and yokes is not uniform, there is a tendency for the flux under the various poles to be uneven. This is especially so on series wound machines. On lap wound machines provided with cross-connectors the effect of cross-connecting points which ought to be at the same potential has the effect of equalizing the pole strength notwithstanding the small inequalities in the reluctance of the magnetic circuit. Nevertheless a very big inequality in the reluctance of the magnetic circuit may call for such large circulating currents through the cross-connectors that these currents, cut down

by the self-induction of the winding, are not sufficient to completely equalize the pole strengths. Whenever the total flux from a pole is less than the normal amount the difference of potential between the positive and negative brushes at each side of the pole is less than normal. That is to say that the loops of the potential curve, Fig. 236, are not of the right height. The case is most marked when there are two poles together whose strength is below normal, because the loss in the voltage is then experienced by both sides of the armature coils which are passing under the poles. This weakening of the two poles sometimes occurs through a bad blow-hole in the yoke. Cast-steel yokes sometimes have very large blow-holes in them, and if the cross-section of the yoke (as designed) is rather small to carry the full flux, a blow-hole may very much reduce the flux of the two poles at each side of the blow-hole. This is more especially so on machines having no cross connections. Another cause of unequal flux from the pole is an inequality in the number of ampere-turns on the pole. Sometimes a shunt coil may be short-circuited or partly short-circuited and a diminution in the flux of the pole may follow as a consequence (see page 30). A shunt coil may be connected in the reverse direction, so that the full ampere-turns are tending to produce a flux of the wrong polarity. So effective are the cross connections on some armatures that even with a reversed shunt coil the machine may operate reasonably well, and the sparking at the brushes may not be so bad as to lead one to suspect such a very serious cause. A measurement of the potential distribution around the commutator will always reveal the dissymmetry due to any of these causes and lead to a detection of the fault. Search coils wound around the poles and connected in opposition to a flux-meter will reveal any inequality of flux.

(4) **Bad spacing of or unequal flux from commutating poles.** As shown on page 265 commutating poles under certain conditions have the effect of increasing the E.M.F. between the brushes. This is more especially so when the brushes are rocked backward on a generator for the purpose of obtaining a compounding effect. If the commutating poles are unevenly spaced or if they are of unequal strength this compounding effect may be unequal, so that the loops of the potential curve are of uneven heights and the current distribution between the brushes affected. Any bad spacing of the commutating poles sufficient to cause an important effect will generally be visible if the main poles are properly spaced. It sometimes happens, however, that the commutating pole winding is short-circuited on one or more poles, and this leads to the result described above. By measuring the milli-volt drop in each commutating pole coil, taking great care to get the voltmeter points on to the actual copper of the coil itself, one can immediately ascertain whether all

poles are uniformly excited. At the same time as this is being done the polarity of the poles can be checked, as the direction of winding of the poles is sufficiently apparent in series coils. It is not likely that the air-gap on commutating poles will be so far out of adjustment as to affect the machine in this respect. The flux may also be affected by heavy currents in cross connectors.

(5) **Irregular spacing of commutator bars.** The irregular spacing of commutator bars produces an alternating effect which cannot be observed on a D.C. instrument, so that while a D.C. instrument may show that the mean continuous current is evenly distributed between the brush-arms, there may be an alternating current superimposed on the direct current producing very heavy instantaneous currents which are too great to be commutated, alternating with instantaneous currents which are too small for the commutating pole adjustment. The tests to discover this alternating effect are described on page 361.

(6) **Unequal resistance in wiring around the frame.** Sometimes on generators designed for very heavy current the resistance of the conductors collecting current from the various brush-arms and conducting it to the terminals of the machine are not of sufficient low resistance, and the voltage drop in these conductors is sufficient to effect the distribution of current in the various brush-arms. This is especially the case where the conductors are built up of strips which are bolted together. There may be a looseness in the joints between the strips causing excessive drop at full load. Where there is an uneven current distribution between brushes which cannot be attributed to any of the causes described above, it is well to take the drop in potential of the various parts of the wiring around the frame to see whether there is any undue drop that will account for the inequality of the current distribution.

After everything has been done to obtain equal distribution of current between the brush-arms and all the matters referred to above have been put in order, the distribution between brush-arms should again be checked over with the brushes rocked to the various working positions. It will sometimes be found that the rocking of the brushes affects the distribution between the brush-arms. This is more especially the case where the potential curves are uneven. There may be different heights and different slopes of the potential curve on parts of the commutator which ought to be equal in those respects, so that the rocking of the brushes may quickly take a brush which is at a low to a higher potential, while another brush which was originally at a higher potential may be on a fairly flat part of the curve and not have its potential changed so much. If this effect of the change of distribution with change of rocking position is at all serious, a complete plot of the potential curve all round the com-

mutator should be taken in the manner described on page 282. This plot of potential curve will usually throw light on the cause of its irregularity, and steps can be taken to remedy the defect.

Adjustment of commutating pole.

Having, then, got the machine to a state in which the current distribution between the brushes is reasonably uniform, say within 10 per cent., over the whole arc through which it may be desired to rock the brushes, we may proceed to adjust the strength of the commutating poles. For this purpose the brushes should be rocked to the position of the commutator on which it is desired that they shall be during full-load operation. As a rule it is desirable to have the brushes on the no-load magnetic neutral. The method of finding the true magnetic neutral at no-load is described on page 279.

Sometimes it is desirable to have the brushes rocked slightly backward, in order to obtain a compounding action (see p. 262). Sometimes it is desirable to have the brushes rocked a little forward in order to get greater stability. Whatever position has been decided upon the commutating poles should be adjusted for that position.

The most usual method of ascertaining whether the adjustment of the commutating pole is right is to measure the drop in potential between the commutator and the brush at various points of the brush from the heel to the toe, as this enables us to get some idea of the current density at various parts of the brush.

Apparatus for measuring brush-drop at various parts of the brush. It is usual to choose four or five evenly spaced points between the toe and the heel of the brush on which to measure the brush-drop. On a narrow brush, say $\frac{3}{4}''$ or narrower, four points as shown in Fig. 289 are generally sufficient. On a wider brush five points may

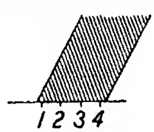


Fig. 289.

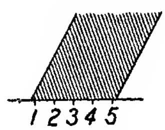


Fig. 290.

be taken as shown in Fig. 290. It is best to take the points near the toe and the heel rather than exactly at the toe and the heel, because we are not quite sure of the position of the extreme points. If we try to go too near the toe or the heel, we may accidentally get into a region outside the contact where the potential difference changes very rapidly per centimetre of periphery.

The guide strip illustrated in Fig. 252 can be used for measuring brush drops. It will be seen in that figure that the holes numbered 10, 11, 12, 13 and 14 are all under the brush; so that if a voltmeter

is connected between the pencil (Fig. 253) and the brush, it will read the voltage drop between the brush and the bar that is passing the hole through which the pencil is pressed.

Another way of measuring the brush-drop at these various points is to prepare two brushes for the four-contact case as shown in Fig. 291. One shape makes contact at points 1 and 4, and the other at points 2 and 3. For the five-contact case three brushes will be required, one for points 1 and 5, another for points 2 and 4, and a third for the central point. These brushes are prepared by filing away the carbon until an edge is left, which, when the brush is placed in the holder, comes down on the commutator on one of the contact points at which it is desired to take the brush-drop. The sides of the brush are ground away so as to leave a clearance of $\frac{1}{16}''$ on all sides between it and the box holder. Cartridge paper, secured

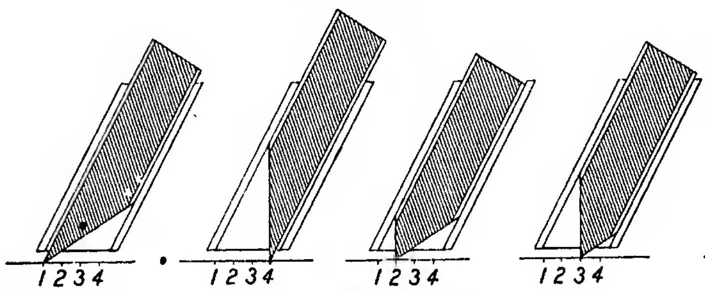


FIG. 291.

by paste, is then wound tightly around the brush to a thickness just sufficient to make it a nice sliding fit in the holder, and to insulate it from the holder. One of the voltmeter wires is then attached to the pig-tail of the brush, and the other terminal of the voltmeter is connected to the brush holder.

It is well to use for this purpose brushes of fairly hard texture, so that the edge is not worn away too quickly. The edge should from time to time be renewed with a file, care being taken to preserve the exact position of the edge. This can be done by drawing a line on the cartridge paper on each side of the brush to indicate the position of the contact edge. In order to take the brush-drop curve on any particular brush-arm, a brush is taken out of one of the holders of that arm and the prepared brush put in its place. A voltmeter, reading to about five volts, is connected between the prepared brush and the brush-arm. An ammeter on series with the armature should be read at the same time as the brush-drop. If the load is unsteady, one should try to read the brush-drop when the armature current is near some pre-arranged value. Small changes in the armature current do not affect the brush-drop appreciably.

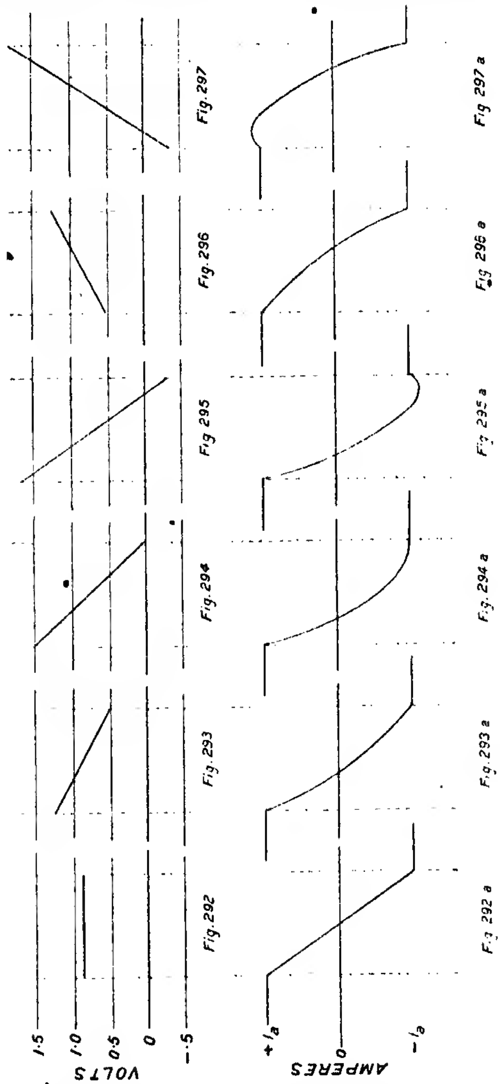
Brush-drop curves. It is very necessary to appreciate exactly what this apparatus measures. Suppose that we have a prepared brush, as shown in Fig. 291, whose edge rests on the commutator near the toe of a line of brushes. This edge touches the commutator bar beneath it for a short interval of time, which commences at the instant that one of the micas flanking the bar passes the edge of the brush and ends at the instant when the other mica passes the edge. During this interval of time, the voltage between bar and brush may change over a considerable range. As we are using a D.C. voltmeter, the reading on the instrument gives the mean potential difference during the interval. Further, it must be remembered that most D.C. generators have several conductors side by side in one slot, each conductor being connected to a separate bar. Suppose that we have eight conductors per slot, there being four conductors side by side and four commutator bars per slot.

As shown in page 259 and Fig. 238, the E.M.F.'s generated in the coils connecting successive pairs of commutator bars are not the same for a given position of the pair of bars with respect to the brush, even when the field form is free from ripples. When ripples are present, the E.M.F. generated in conductors immediately after they have passed the neutral zone may be changing fairly rapidly; so that while the potential of bar No. 1 when it passes the toe of the brush may be only 0·5 volt above the potential of the brush, the potential of bar No. 4 may be 1·5 volts above that of the brush when it reaches the same point. The voltmeter then reads the mean value of the potential difference taken throughout the whole interval of time required for the four bars to pass. The oscillograph curves given in Figs. 308 to 310 show over what a wide range the instantaneous values of the brush-drop may change in certain cases.

Brush-drop curves in ideal machine. If we could have an ideal machine with extremely narrow bars and uniformly spaced conductors moving in a commutating field of constant strength, then it is clear that the best form of the brush-drop curve would be a straight line, as shown in Fig. 292. The height of the ordinates, shown as 0·85 volt in this figure, would of course depend on the kind of brush, the current density, and the other matters considered on pages 302 to 316. Such a curve would indicate that the current density was uniform all over the brush face; and a uniform current density gives us the least losses.

If the brush drop measured on the ideal machine were of the shape shown in Fig. 293, it would indicate that the current density was much greater at the heel of the brush than at the toe. The current density is not proportional to the brush-drop, so that we cannot tell by how much the current density at the heel exceeds that at the toe. We cannot even make use of the brush curves,

such as those given in Fig. 258, because a higher current density at one part of a brush will in a very short time cause the length of the



Brush-drop curves and the corresponding commutation curves.

arc between brush and commutator to become slightly greater at that part than at the part where the density is less; and this uncertain increase in the length of the arc affects the amount of the brush-drop.

After a machine has been running on load for a long time and the brushes have become worn and burnt on their face to their final working shape, it is probable that the curve of brush-drop represents much more nearly the curve of current density than it does when the brushes are newly bedded in; but in any case there is no proportionality between the ordinates of the brush-drop curve and the ordinates of the current density curve.

Relation between current density and rate of change. In our ideal machine the current density is directly proportional to the rate of change of the current * in the coil under commutation. The brush-drop curve can thus be taken as some indication of how quickly the current is changing in the coils at different points along the brush face. A curve like that in Fig. 292 tells us that the current is changing at a uniform rate, just sufficient to bring about straight-line commutation (see Fig. 292*a*), and thus produces uniform current density over the face of the brush.

A curve like that shown in Fig. 293 tells us that current density is greater than it should be under the heel of the brush, and that the current is changing more quickly at this point than is necessary for straight-line commutation. Now the total change of current in the coils is fixed for a given load, so that if the rate of change is too great at the beginning of the interval it is bound to become smaller at a later point of the interval, if the average is to be maintained. Or, looking at the matter from the point of view of current density; if the density is greater than the mean at the beginning of the interval, then it must be smaller than the mean at a later point of the interval. A commutating pole that is too strong causes the current to change too quickly at the beginning of the commutating period, so that we have early commutation, as shown in Fig. 293*a*. Note that the slope of this curve does not get to zero until the commutation period is over, and the corresponding brush-drop curve given in Fig. 293 does not fall to zero.

If the inter-pole is made still stronger, the commutation curve may assume a shape like that shown in Fig. 294*a*, in which the rate of change of the current in our ideal coils is zero just before the end of the commutating period. This would mean that the current

* *Proof.* Let dx be a small distance on the surface of a brush that is passed by a point on the commutator in a small time dt. Let l be the axial length of the brushes. Then $l.dx$ is a small area of the brushes swept by a line on the commutator in the time dt. Let i_d be the current density; so that $i_d l.dx$ is the current yielded to the brush over the small area in question. This current yielded to the brush is the difference dI between the value of the current in the coil at the beginning of the interval dt and the current in the coil at the end of that interval.

Therefore $$i_d l \cdot dx = dI,$$

or $$i_d l \cdot \frac{dx}{dt} = \frac{dI}{dt} = i_d l v,$$

where v is the peripheral velocity of the commutator.

density would be zero at the end of the period, so that the brush-drop curve might assume a shape like that shown in Fig. 294.

If the inter-pole is made still stronger, we shall get over-commutation in which the current in the coils assumes a greater negative value than it will have after the toe of the brush is passed (see Fig. 295a). It is therefore necessary for the resistance of the brush or the spark at the toe to bring back the current to its normal value. This means that the rate of change of the current in the final stage of the commutating period must be in the opposite sense, and that the current density near the toe of the brush must be in the opposite sense. The brush-drop curve may then take a shape like that shown in Fig. 295.

In case the inter-pole is too weak, the reversing of the current is delayed. The commutation curve may then be like Fig. 296a, and the brush-drop curve like Fig. 296. If the excitation of the commutating pole were so weak as to be overpowered by the armature ampere-turns, the inter-pole flux would be in the wrong sense, so that the commutation curve and brush-drop curves might assume the shapes shown in Fig. 297a and Fig. 297 respectively.

Departure of ordinary machines from ideal performance. This consideration of the shapes of brush-drop curves of an ideal machine gives us a guide to the interpretation of the brush-drop curves as found on ordinary machines. We must, however, never forget the differences in the curve shapes caused by the facts that the commutator bars are not infinitely narrow and the coils are not uniformly distributed.

Effect of the finite width of the bars. The statement that the current density is proportional to the rate of change of the current in the coils under commutation is completely true only in the ideal case where the bars are so narrow that any bar under consideration lies wholly under a brush. Where the bars have finite width and part of a bar passes from under the brush, the current density depends not only upon the total current yielded by the bar, but also upon the area of contact at the instant in question. As the bar of finite width moves forward, the area of contact is gradually reduced to zero; so that, whatever finite current the bar is yielding to the brush the current density must rise to infinity before the bar leaves the brush. This progressive increase of the current density and consequent rise of brush-drop has a most salutary effect in correcting small errors in the adjustment of the commutating pole.

If the pole adjustment is such as would leave a finite current flowing from bar to brush at the instant of breaking contact, the rising brush-drop, acting as a back pressure, forces the current down to zero before the circuit is broken, and bad sparking is prevented. There is, of course, a limit to the correcting pressure capable of being

exerted by the brush. One should not call upon the brush to exert a correcting voltage of more than two volts, or some sparking will result. With very hard carbon brushes of high contact resistance, errors of commutating pole adjustment calling for a correcting pressure of 3 volts or more, have been successfully combated; but it is better not to throw such an arduous duty upon the brush.

The Effects of the grouping of the conductors in slots are considered on pages 258 to 261, and 263 to 265. It will be seen that the volts generated in a coil joining a pair of bars is not constant as between successive pairs of bars for a given position of a pair with respect to the brush. It follows that no given adjustment of the commutating pole can be exactly right for all bars. We can only hope to make a compromise, and the excitation which is found best in practice is in reality rather too strong for some coils and rather too weak for others. If the commutating pole is on the whole too weak there is a tendency (as explained on page 359) for the main work of commutation to be left over for the last coil of the group. If, on the other hand, the pole is too strong then the last coil of the group may be left with surplus negative current and may be unable to get rid of it without a spark.

As some bars leave the toe of the brush there will be a tendency for the current from it to reverse; while with other bars there will be a tendency for the current to flow too long and draw out a spark. These tendencies are in most cases corrected by the resistance of the brush contact, so that sparking does not result.

"Half-stepped windings." The fluctuation of the value of the voltage generated between bars at any given point of the commutator can be very much reduced by "half stepping" the winding. By this is meant the splitting up of a group of coils whose "bottom" coil-sides lie on the bottom of one slot so that their "top" coil-sides lie some in the top of one slot and some in the top of another slot. Thus if the bottom coil-sides of coils 1, 2, 3 and 4 lie in slot No. 1, we may place the "top" coil-sides of 1 and 2 in the top of slot No. 12, and the top coil-sides of 3 and 4 in the top of slot No. 13.

The effect of this in smoothing down the irregularities illustrated in Figs. 238 and 240 will be understood from an examination of Table V., which is compiled from the same figures for average volts between bars as given on page 259. It will be seen that there are now only two bars that have the same voltage between them and that voltage in the case of two of the bars is the mean of the voltage generated in two different slot positions. Thus in the first position 2 and 3 have the values 0·41 ascribed to them. This is because one of the coil-sides joining them has 0 volt and the other coil-side has 0·82 volt.

When we make a summation of the figures in Table V., we arrive at the potential distribution curves shown in Fig. 298. It will be seen that the fluctuation of the voltage at any distance from the neutral is very much diminished below the extremes shown in Figs. 238 and 240. This improvement brought about by the half-stepped winding is of special importance when there are tooth-ripples in the E.M.F. wave-form in the vicinity of the neutral.

TABLE V.—VOLTAGES BETWEEN BARS OF COMMUTATOR IN VARIOUS POSITIONS.
Four Commutator Bars per slot. Half-stepped Winding.

No. of Ordinate	-3	-2	-1	NEUTRAL	1	2	3	4	5	6	7	8	9	10	11	
No. of Bar	-3	-2	1		1	2	3	4	5	6	7	8	9	10	11	12
1st Position	-0·41	-0·41	0		0	0·41	0·41	0·82	0·82	4·3	4·3	7·8	7·8	10·1	10·1	13·4
2nd Position	-0·5	-0·21	-0·21		0·08	0·08	0·69	0·69	1·3	1·3	5·6	5·6	10	10	12·2	12·2
3rd Position	-0·25	-0·25	0		0	0·25	0·25	1·175	1·175	2·1	2·1	6·8	6·8	11·5	11·5	12·9
4th Position	-0·69	0·08	0·08		0·21	0·21	0·5	0·5	2·25	2·25	4	4	8·25	8·25	12·5	12·5

Drooping curve towards the toe. We have seen that on the ideal machine a level brush-drop curve (see Fig. 292) would indicate perfect adjustment of the commutating pole. It is common knowledge, however, that on commercial machines the curve that gives the least sparking is not as a rule a level curve, but one that droops somewhat towards the toe. The reason for this is to be found in the effects mentioned in the two preceding paragraphs. If the commutating pole is adjusted so as to give a very small mean current density at the toe of the brush during the last stage of the commutation, any departure from uniformity, in the direction of excessive current density on some bars, will be met more easily by the brush resistance if the mean density is zero, than if the mean density has a finite positive value. This is more particularly so because of the law of change of voltage drop with current density, as illustrated in Fig. 258.

Practical test. While the brush-drop curve serves as a guide and enables us to get some idea of the distribution of current on the face of the brush, the real criteria of correct inter-pole adjustment, is the absence of sparking. Some low voltage generators permit of a wide range of adjustment of the inter-pole, without showing any sparking. In these cases the inter-pole should be adjusted so as to give the lowest temperature rise. An adjustment which gives a fairly level brush-drop curve gives the lowest brush losses. If it is found that the sparking is least when the brush-drop curve is of the kind shown in Fig. 294, we may conclude that the brush-drop

exerted by the brush. One should not call upon the brush to exert a correcting voltage of more than two volts, or some sparking will result. With very hard carbon brushes of high contact resistance, errors of commutating pole adjustment calling for a correcting pressure of 3 volts or more, have been successfully combated; but it is better not to throw such an arduous duty upon the brush.

The Effects of the grouping of the conductors in slots are considered on pages 258 to 261, and 263 to 265. It will be seen that the volts generated in a coil joining a pair of bars is not constant as between successive pairs of bars for a given position of a pair with respect to the brush. It follows that no given adjustment of the commutating pole can be exactly right for all bars. We can only hope to make a compromise, and the excitation which is found best in practice is in reality rather too strong for some coils and rather too weak for others. If the commutating pole is on the whole too weak there is a tendency (as explained on page 359) for the main work of commutation to be left over for the last coil of the group. If, on the other hand, the pole is too strong then the last coil of the group may be left with surplus negative current and may be unable to get rid of it without a spark.

As some bars leave the toe of the brush there will be a tendency for the current from it to reverse; while with other bars there will be a tendency for the current to flow too long and draw out a spark. These tendencies are in most cases corrected by the resistance of the brush contact, so that sparking does not result.

"Half-stepped windings." The fluctuation of the value of the voltage generated between bars at any given point of the commutator can be very much reduced by "half stepping" the winding. By this is meant the splitting up of a group of coils whose "bottom" coil-sides lie on the bottom of one slot so that their "top" coil-sides lie some in the top of one slot and some in the top of another slot. Thus if the bottom coil-sides of coils 1, 2, 3 and 4 lie in slot No. 1, we may place the "top" coil-sides of 1 and 2 in the top of slot No. 12, and the top coil-sides of 3 and 4 in the top of slot No. 13.

The effect of this in smoothing down the irregularities illustrated in Figs. 238 and 240 will be understood from an examination of Table V., which is compiled from the same figures for average volts between bars as given on page 259. It will be seen that there are now only two bars that have the same voltage between them and that voltage in the case of two of the bars is the mean of the voltage generated in two different slot positions. Thus in the first position 2 and 3 have the values 0·41 ascribed to them. This is because one of the coil-sides joining them has 0 volt and the other coil-side has 0·82 volt.

is oscillatory in character. This may be confirmed by taking readings on an A.C. voltmeter, as well as on a D.C. voltmeter. The difference between the squares of the readings then gives us the square of the virtual value of the superimposed oscillation. In cases when this oscillation proves to be of a serious character its cause must be determined (see page 359), and eliminated.

Diverter for inter-pole winding. The most usual method of changing the strength of the inter-pole for any given load, say, full load, is to divert part of the current from the winding by means of a german-silver strip or iron grid, connected in parallel with it. It is a good plan for the tester to provide himself with a universal diverter, consisting of a large number of strips mounted on a frame and arranged so that any number at will may be connected in parallel. This diverter may be connected to the terminals of any inter-pole winding by means of low-resistance flexible cables, and the parallel strips switched in and out until the best effect is observed. The correct resistance for the diverter is then at once apparent from an inspection of the strips in parallel, so that a permanent german-silver strip can be made up for attachment to the machine.

Effect of temperature. One objection to a diverter made of german-silver, or any metal with a low temperature coefficient, is that, when the machine gets hot, a larger proportion of the current is diverted than when the machine is cold. The small difference in the inter-pole strength made by this circumstance is not usually in itself sufficient to affect the practical operation of the machine, but it may combine with other effects (see page 347) that tend to make the inter-pole too weak on heavy load. If the diverter be made of iron, having a high temperature coefficient, it will tend to divert less current as the machine and diverter get warmer, so that when the machine is working on a steady overload the commutating pole will receive a rather larger proportion of the current than at light loads, and some compensation is made for the higher saturation of the pole. Where the load is of a fluctuating character, one cannot make use of this method of compensation, because the diverter takes many minutes to reach its final temperature at given load.

Fluctuating loads. Generators supplying a traction load where the demand for a heavy current may come on very suddenly, sometimes spark badly as the load increases, because the increase in the magnetic field provided by the commutating pole lags behind the increase in the current. This may be due to the demagnetizing effects of eddy currents, set up in the solid metal of the commutating poles, as the ampere-turns on the poles increase. Solid poles are more liable to this trouble than laminated poles. Any damper on the pole tends to increase the effect, or the lag may be due to the difference in the time constants of the diverter and commutating

pole circuits. The inductance of the commutating winding may be very considerable, whereas the inductance of a german-silver diverter is very small. When the load increases suddenly, the first rush of current finds a much easier path through the diverter than through the commutating pole. Sometimes when a diverter is used it is provided with a choke coil in series with it, so as to increase the inductance of the diverter circuit. If the ratio of the resistance to the inductance is made the same for the two circuits, the current will always divide according to the inverse ratio of the resistances, however the load may fluctuate.

Where an inductive diverter circuit is provided it is usual to make the ratio $\frac{R}{L}$ for the diverter rather less than for the commutating pole, so as to neutralize the lagging effect brought about by the eddy currents in the solid parts of the poles. The simplest method of dealing with heavy fluctuating loads is to provide laminated inter-poles with large air-gap (preferably behind the pole, see page 349), and adjust the strength of the pole by adjusting the length of the air-gaps so that no diverter is needed.

Effect of saturation of the inter-pole. The inter-pole is rather liable to become saturated on heavy loads. The useful working flux from the pole is itself small, the density in the air-gap under the pole being commonly only from 2000 to 4000 C.G.S. lines per sq. centimetre. The leakage flux, however, may be very heavy. This is due to the very large number of ampere-turns which the pole must carry in order to overcome the armature ampere-turns and the small clearances between the inter-pole and the main pole on frames which have been rated to their maximum output. It must be remembered too, that the effective ampere-turns available for driving the working flux across the air-gap and along the iron parts of the inter-pole magnetic circuit is only the difference between the ampere-turns on the pole and the ampere-turns on the armature. This difference may only amount to one or two thousand ampere-turns, so that a few hundred ampere-turns absorbed on the iron parts of the magnetic circuit may make a very considerable deviation from the proportionality between the flux and the effective ampere-turns.

This matter is more easily understood if we take a quantitative example. Consider the case of a 500 K.W. 500-volt D.C. generator, having 8 poles and 96 conductors per pole equivalent to 48 turns per pole. The full load current per conductor will be 125 amperes, so that the armature ampere-turns will be 6000. Let us suppose that it requires a flux density of 4000 in the gap under the inter-pole to bring about good commutation at full load, and that an effective M.M.F. equivalent to 2500 ampere-turns on the inter-pole are required to produce this flux density.

Further, let us suppose that there is some saturation of the inter-pole circuit, so that the relation between flux density in the gap and effective ampere-turns is given by the curve B in Fig. 298a. Let the straight line OA give the relation between the load and the flux density required in the air-gap to bring about the best commutation.

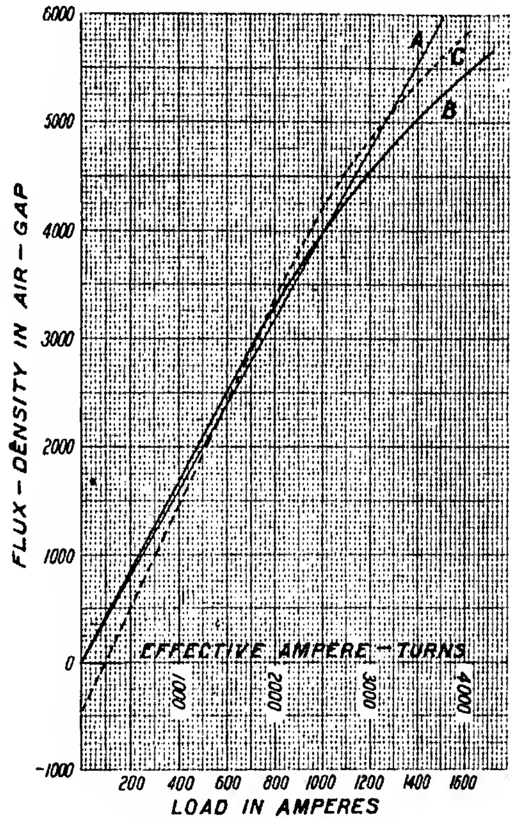


FIG. 298a.—Characteristic curve of a commutating pole provided with a reversed shunt winding.

It will be seen that if we have nine turns on each inter-pole, and divert 5·5 per cent. of the current we will have 9000 − 500 = 8500 ampere-turns on the inter-pole at full load. Subtracting 6000 from this we get 2500 effective ampere-turns, or just exactly the right amount to give us the required 4000 c.g.s. lines in the gap to bring about good commutation. Now let the load increase to 1500 amperes. The density in the gap will become 5250 instead of 6000 required for

good commutation. As the difference is over 12 per cent. the sparking may be quite bad, and there may be a tendency to flash over if the load increases.

The best way of curing a trouble of this kind is by adopting the double brush described on page 351, and a very good palliative is the reduction of the magnetic leakage by putting a wide air-gap behind the inter-pole. If it is not convenient to apply these remedies the commutation can be made a good deal better at 1500 amperes by diverting less current, thus making the inter-pole a little too strong at full load, but not so much as to spoil the commutation.

Auxiliary shunt winding on inter-pole. A still more effective palliative is to take away the diverter altogether and add a small shunt coil to each inter-pole capable of giving about 300 ampere-turns opposed to the series ampere-turns. At a load of 1500 amperes the effective ampere-turns on the inter-pole will be 13500 − 9000 − 300 = 4200. This will give us a flux density of 5600 in the gap, that is only 6·5 per cent. too small, while at full load the flux density is only 5 per cent. too great. See curve C of Fig. 298a. The fact that we have a slight negative excitation at no-load is of no moment, because apart from the fact that this is opposed by the residual magnetism of the pole it is too weak to cause deleterious circulating currents in the brushes. One advantage of the small shunt coils on the inter-poles is that by means of a rheostat in circuit with them we have such a convenient method of adjusting the excitation of the pole while the machine is running, whereas the alteration of a diverter as ordinarily supplied with a big machine is not so convenient.

Methods of reducing the leakage on inter-poles. The saturation of the iron of inter-poles is mainly caused by the great magnetic leakage which ordinarily occurs on them (see page 346). Any arrangement of the parts which reduces magnetic leakage helps to keep the commutating flux proportional to the load. The exciting winding should be arranged so as to exert its M.M.F. as near as possible to the part that is to be magnetized.

For this reason the turns of a compensating winding distributed over the face of the main poles are more effective than the same number of turns placed on the inter-pole itself because they neutralize the armature ampere-turns in situ, and do not give rise to much magnetic leakage. The expense of the compensating winding precludes its use in ordinary commercial machines. The next best plan from the magnetic point of view is to make the commutating coil winding as short as possible in a radial direction, as to put it as close as possible to the armature (see Fig. 299). This arrangement unfortunately somewhat blocks the natural ventilation of the field system, and is therefore not adopted except on machines having

wide spaces between the poles. While it is necessary on most commercial machines to give the coils a considerable radial length in order to find room for all the required ampere-turns and air-space for the cooling, the radial length should not be made any greater than is absolutely necessary, and the coil should be supported as near to the armature as is consistent with good mechanical construction. The part of the pole between the coil and the yoke should be made of sufficient section to carry its maximum magnetic flux at a density not exceeding 13,000 C.G.S. lines per sq. cm.

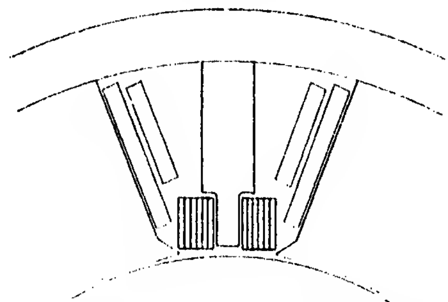


FIG. 299.—Commutating coil of short radial length to keep down leakage.

The air-gap between the armature and the inter-pole should be made as small as possible, consistent with the elimination of tooth ripples. If the teeth are skewed and the corners of the pole bevelled, this air-gap may be reduced to quite small dimensions without introducing tooth ripples. It is then possible to make quite a long air-gap between the root of the pole and the yoke. The object of this gap is two-fold. In the first place, it calls for more effective ampere-turns on the pole. It is not well to have the effective ampere-turns too small a fraction of the armature ampere-turns. For machines on which the commutating conditions are easy we may have the fraction as low as 0·2, but where the conditions are difficult it is better to make it nearer 0·4.

By making an air-gap behind the inter-pole we can fix the gap between it and the armature at any value we wish so as to secure good magnetic screening and then make up the required demand for ampere-turns by adjusting the other gap.

The second advantage is that for a given number of ampere-turns on the pole, the magnetic leakage is less where there are two gaps than where there is only one next to the armature. Any leakage from the sides of the inter-pole, due to the difference of magnetic potential between it and the yoke, is negative leakage, and it must be subtracted from the positive leakage which occurs at

the other end of the pole (see Fig. 300). The negative leakage is not so easy to get on D.C. generators and motors as it is in synchronous converters, because in the former there must always be a very large proportion of the total M.M.F. opposed to the armature M.M.F. and this will produce positive leakage, whereas on a synchronous converter

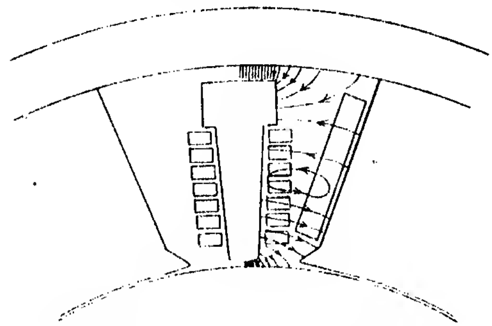


FIG. 300.—Wide air-gap behind inter-pole to increase the ampere-turns on the pole without increasing the leakage.

a much smaller proportion of the total M.M.F. is opposed to the armature reaction.

Automatic adjustment of commutating pole. A simple method of making the commutating pole winding automatically adjust itself to the varying conditions of the load is as follows.

Arrange half the brush-holders on each arm so that they are about $\frac{3}{8}$ inch in advance of the remainder of the arms, as shown on

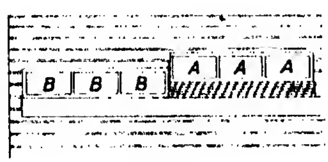


FIG. 301.

Fig. 301, and are lightly insulated from the arms. This can be sometimes done by putting a packing piece of thick fuller board between the holders and the arm and providing the bolts that secure the holders with suitable insulating bushes. Two new bus-rings can then be fixed around the brush-rocker and the current from the insulated brushes fed into these rings. Let us denote the positive brush holders that are $\frac{3}{8}$ inch forward by A and the backward holders by B. On the negative arms let the forward brushes be A' and the backward B'. We may then connect the brushes to the

load in the manner indicated in Fig. 302, where W and W' are commutating pole windings, and D is a resistance of approximately the same value as W. It will be seen that only the current from the A and A' brushes goes through the commutating pole winding. The coils must therefore have twice the number of turns as would be required if the whole current passed through them, and the cross-section of the copper strap may be only one half as great. With this arrangement the current divides between the sets of brushes A and B, so as to keep the commutating pole at the right strength. If the pole is too strong, the B set will tend to get more current than the A set (see Fig. 294), and this will reduce the excitation.

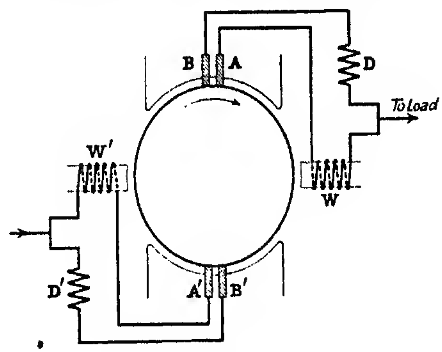


FIG. 302.—Connections of double brush for automatic adjustment of commutating pole.

If the pole is too weak the A sets will tend to get more current than the B sets (see Fig. 296) and this will strengthen the commutating pole. It is found in practice that the automatic control which this arrangement gives is so powerful that even if a deliberate attempt is made to interfere with the current distribution by short-circuiting D or by increasing the resistance D to several times the resistance of W, only a very small change in the distribution is made. The little change that does occur is sufficient to almost counteract the effect of the unequal distribution of resistance. This is because the drop in voltage in commutating-pole windings on machines of any size is usually small compared with the voltage under the brushes.

The arrangement also works well on machines subjected to sudden overloads. On an ordinary machine the commutating pole may fail to respond quickly enough to commutate the quickly rising current, but with this arrangement any weakness of the pole causes the current to be carried forward to the A sets of brush holders, and before bad sparking can occur the current in the commutating pole will rise to nearly double of its normal value. In this case the

inductance of the armature coils under commutation is pitted against the inductance of the inter-pole winding and forces the current through this winding notwithstanding the alternative path through D. The most powerful effect is obtained by arranging the A and B brushes of suitable width and putting the A brushes completely ahead of B, but not so far ahead that a commutator bar leaves the B brushes before touching an A set. One good feature of this arrangement is that it neutralizes any of the tendencies (such as mentioned on pages 340 to 342) towards the production of eddy currents flowing from the toe to the heel of the brushes. Such an eddy current would have to pass through the commutating pole, and the magnetic field set up would generate an E.M.F. opposed to the E.M.F. producing the eddy.

Double-commutator machines. Sometimes a D.C. generator, designed to deliver a current of many thousands of amperes, say, for electrolytic work, is provided with two commutators, one at each end of the armature. The equal division of the current between these two commutators is usually carried out by very careful rocking of the brushes at each end. A very small disturbance of the brush position may throw a very heavy load on one end of the machine. Sometimes resistances are inserted with the cables from each end to make the equalization more stable. A very simple way of stabilizing the current distribution is to connect only the brushes at one end of the machine in series with the commutating pole.

These brushes can then be rocked forward by a suitable amount, and automatic adjustment of the current between the two sets is brought about by the action of the commutating pole as explained above.

OTHER DEFECTS IN THE COMMUTATION OF D.C. GENERATORS.

On most modern machines, the adjustment of the brushes for good collection of current, the equalization of the current between the brush-arms, and the correct adjustment of the commutating poles, are all that is necessary to bring about good commutation. It may be, however, that after these matters have been attended to it is still found that the machine sparks on load, so that it is necessary to look for other causes of trouble.

An oscillograph is of great service in throwing light upon the behaviour of the machine. In Chapter XVI. page 428, some hints are given upon the use of the oscillograph.

Ripples on the wave form.

Fig. 303 shows the no-load wave form of the E.M.F. in an armature coil on a D.C. generator having twenty-three slots per pole. Its main

outline follows the field form of the flux from the pole. Superimposed upon this main outline are a number of tooth ripples.*

It is well here to consider some of the causes of these ripples. In the first place, it should be said that tooth ripples may be divided

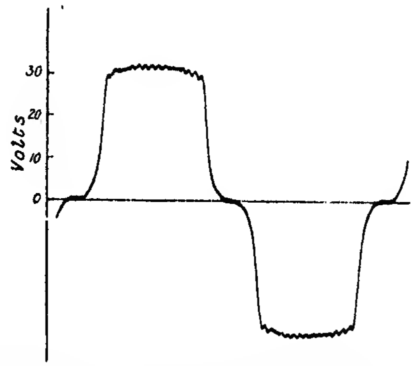
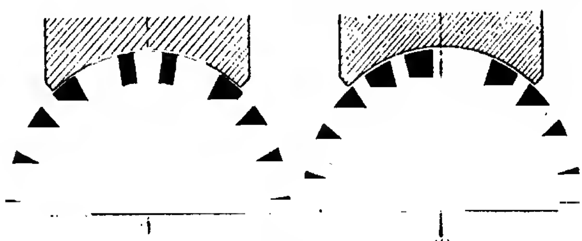


FIG. 303.—No-load wave-form of E.M.F. in one coil of D.C. generator having 23 armature slots per pole. The irregularity in the ripple is an interference effect due to slots in the pole face. Time scale 1 cm. = 0·0027 sec. Frequency 67·7.

into two classes: those due to swinging of flux and those due to pulsation of flux.

Swinging of flux. As the teeth of the armature in Fig. 304 (which shows for simplicity only eight teeth per pole), change from position (*a*) to position (*b*), the magnetic flux cuts across the conductors



(*a*) FIG. 304. (*b*)

lying in the slots. Beginning with position (*a*), and considering the armature as moving clockwise: the first effect is for the five teeth to carry most of the flux with them, so that the flux distribution is unsymmetrical about the central line of the pole, the deflection being

* M. B. Field, "A Study of the Phenomena of Resonance in Electric Circuits," *Journ. I.E.E.*, vol. 32, p. 647; G. W. Worrall, "Commutation Phenomena and Magnetic Oscillations occurring in D.C. Machines," *Journ. I.E.E.*, vol. 45, p. 480; S. P. Smith and Boulding, *ibid.* vol. 53, p. 205, 1915.

to the right. When position (*b*) is reached, the new tooth approaching the pole on the left takes the same amount of flux as the tooth leaving the pole on the right, and the flux again becomes symmetrical. A slight continuation of the clockwise motion gives again a dissymmetry of the flux distribution about the central line; but now it is the new tooth and the four under the pole that claim the main bulk of the flux, producing a deflection to the left. Thus the flux swings backward and forward relatively to the pole as the teeth revolve, and in cutting across the conductors sets up an E.M.F. that is one of the main causes of the tooth ripple. If the swinging of the flux of the main poles only be considered, this E.M.F. is at a maximum in the conductors directly under the pole, and is zero in the conductors in the neutral plane. This can be seen from an inspection of Fig. 303. The same action, however, occurs under

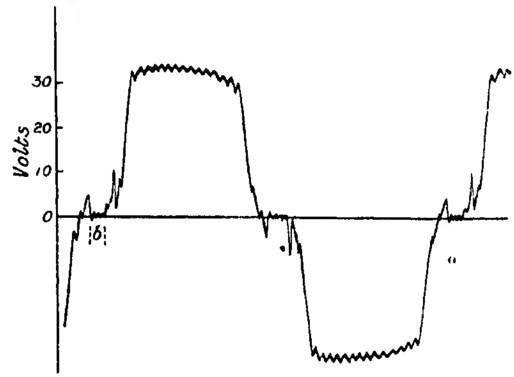


FIG. 305.—Full-load wave-form of E.M.F. in one coil of D.C. generator having 23 armature slots per pole. Time scale 1 cm. = 0·0026 sec. Frequency 67·7. The dotted lines at *b* show the width of the brush (see p. 327).

the commutating poles, when these poles are excited with the load current, and the swinging of the commutating pole flux produces its maximum effect in the coils under commutation. The swinging of the flux of the commutating poles is more complex in character than the swinging of the main flux, because it is due not only to the variation of the path of the flux when the teeth change their position but also to the change in the M.M.F. exciting the path as the currents in the conductors change their value. Fig. 305 gives the full-load wave form of the E.M.F. in one coil of the D.C. generator to which Fig. 303 referred. The generator was provided with a compensating winding, which was rather stronger than the armature, so that the main flux is distorted slightly against the direction of rotation. It will be seen that there are very pronounced ripples near the centre of the commutating pole (see p. 357); but while the coil is main

circuited by the brush (see region marked *b*), the ripples are suppressed. Fig. 306 gives an oscillogram of the brush-drop at full-load, taken between the bar near the centre of the brush and the brush holder. The irregularities were due to uneven spacing of the bars and repeated themselves faithfully at each revolution.

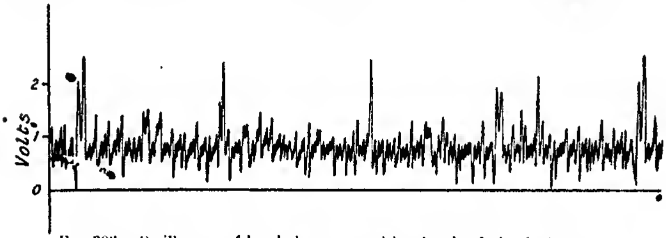


Fig. 306.—Oscillogram of brush drop on positive brush of the D.C. generator referred to in Figs. 303 and 305. The oscillogram includes a complete revolution of the commutator (4 poles) and begins to repeat itself. There were 23 commutator bars per pole. This being an odd number we have 46 current breaks in the half cycle. The current break under a negative brush shows itself by inductive effect under the positive brush (see p. 357). Time scale 1 cm. = 0·003 sec.

When there are slots in the pole having the same pitch as the armature slots the tooth ripple becomes very pronounced. Where the slots in the pole have not exactly the same pitch it will be found that at certain positions of the armature the ripple is pronounced and at other positions it disappears due to an interference effect. This effect is visible on the no-load curve, Fig. 303, but is not so visible in the full-load curve, Fig. 305, where the magnetized teeth of the armature had a more powerful effect.

The pulsation of the E.M.F. caused by the pulsation of the main pole flux causes a tooth ripple in the E.M.F., and this in general gives rise to a ripple in the direct current (see Figs. 317 and 319). This ripple in the current changes the strength of the commutating poles from instant to instant.

Pulsation of flux. The main flux from the pole cannot pulsate through a great amplitude, because the currents induced in the shunt coil acting as the secondary of a transformer, and also in the solid parts of the magnetic circuit, tend to wipe out any pulsation. Nevertheless, small pulsations of the flux embraced by the coils under commutation can be observed; and as very small pulsations are sufficient to set up E.M.F.'s seriously affecting commutation, this cause of trouble must not be neglected.

There are two main causes of flux pulsations through the armature: (*a*) ripples in the main current, produced by tooth ripples, which in turn may have their origin in flux-swinging; (*b*) variations in reluctance of the magnetic circuit, due to the passage of the teeth under the pole horn from position (*a*) to position

(b) in Fig. 304. Of these, undoubtedly the first is the more important.

Thus we see that while flux-swinging under the main poles cannot directly set up E.M.F.'s in the coils under commutation, it may, through the medium of ripples in the armature current, superimpose upon the magnetic circuit an alternating M.M.F. which is of sufficient amplitude to set up pulsations in the flux embraced by coils under commutation. Moreover, the ripples in the main current set up variations in the M.M.F. exerted by the conductors under the commutating poles, and thus affect the distribution of the commutating flux. The whole action is exceedingly complex, and is hardly amenable to analytical investigation, because so much depends upon the irregular changing of the reluctance of flux paths as the teeth change their position under the main poles and the commutating poles.

Mutual induction between coils. There is also another source of E.M.F. in the coils under commutation. When for any reason the commutating pole is not adjusted so as to reduce the current passing from a bar to the toe of the brush to zero at the instant when the bar leaves the brush, the current must be broken suddenly as the circuit is opened. The sudden change in the value of the current in the coil leaving the brush sets up by transformer action an E.M.F. in the adjacent coils, and the current in the other coils lying in the same slot changes just as suddenly but in the opposite sense.

Sparkographs. The mutual induction between the coils reduces the self induction of the coil leaving the brush; so that the bad spark which would otherwise occur is suppressed or minimized, but the suppressions of the spark may lead to a very sudden change in the current density on the surface of another bar which is still under the brush. This change of current density may be so sudden and so severe for a short interval of time that the short arc under the brush may leave, after a few hours' run, a pattern on the face of the brush in which the widths of the bars and even of the mica can be discerned. These pictures on the face of the brush may be called "sparkographs." They are most commonly rather blurred, owing to the movement of the bars while the picture is being printed; but in rare cases they are most wonderfully sharp, the picture of the mica segment being perhaps not more than $\frac{1}{16}''$ wide.

Such sharp pictures could only be produced if the change in the value of the current density is extremely sudden. It may be that the small capacity that exists between the different turns of an armature winding assists in the sudden breaking of the current as a bar leaves the brush and the sudden transfer of the energy to the next armature coil.

That E.M.F.'s of great suddenness do occur in armature windings

when a brush is sparking or is near the sparking limit, is shown by the oscillogram given in Fig. 307. This oscillogram was taken on a two-pole D.C. machine having 18 slots and 54 commutator bars. One of the armature coils had its terminals connected to two slip-rings and the voltage between the rings was recorded by the oscillograph as the machine ran on load. The general shape of the field form of the generator appears in the oscillogram; but superimposed upon this field form are violent oscillations, which have the frequency of the commutator bars. These are produced by the transformer action between the coils leaving the brush and the coil connected to the slip-rings. The oscillations are greatest when the mutual inductance is greatest, and fall to zero when the slip-ring coil is at right angles to the coils under commutation. It will be seen that the voltage induced by the breaking of the current at the toe of the

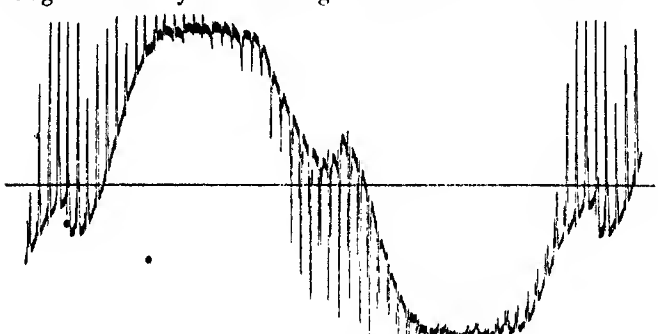


FIG. 307.—Wave form of E.M.F. generated in one coil of a two-pole D.C. generator having 54 commutator bars. The brushes were badly bedded and sparking on load.

brush has an amplitude as great as the voltage generated by the movement of the coil under the main pole. It is greatest when the coil is at right angles to the axis of the main poles, but is not so apparent at the terminals of the coil while it is short-circuited by the brushes, because it is then absorbed in driving current through the coil. The effect here described is perhaps the most potent cause of the ripples near the neutral in the full-load wave form of E.M.F. generated on a single turn on the armature of the D.C. generator referred to in Fig. 305.

Variation of voltage due to spacing.

The effect of ripples must be taken in conjunction with what was said on page 259 with regard to the changes of potential difference between commutator bars as a slot takes up different positions in the field. It will be seen from Table III. and Fig. 238, that variations in the potential difference between bars may be of considerable

magnitude, even when the field form sinks gently to zero at the neutral plane. If now we superimpose upon the smooth field form ripples of sufficient magnitude to change substantially its slope

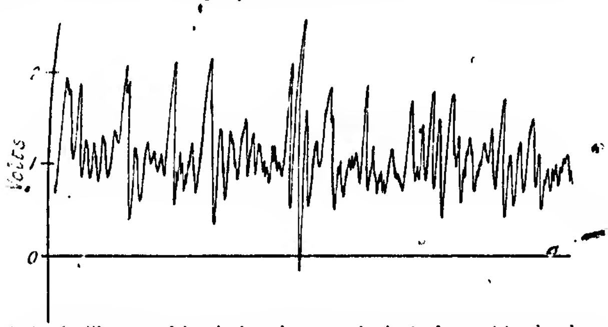


FIG. 308.—Oscillogram of brush drop between the heel of a positive brush and the commutator of a synchronous converter on load. Time scale 1 cm. = about 0·005 sec.

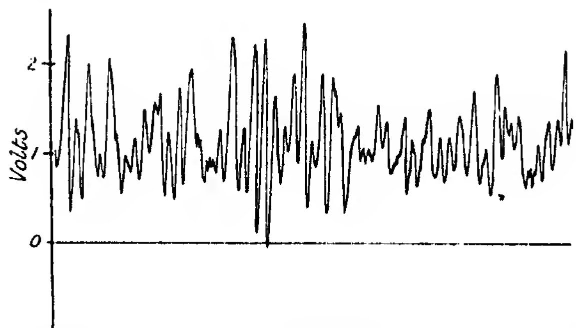


FIG. 309.—Oscillogram of brush drop between the middle of a positive brush and the commutator of a synchronous converter. Time scale 1 cm. = about 0·005 sec.

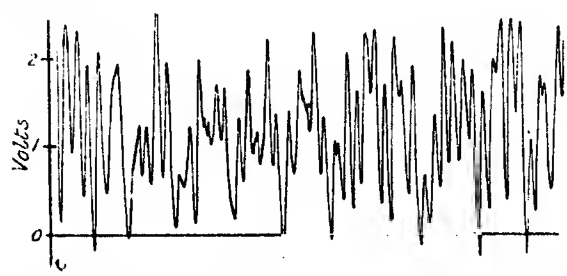


FIG. 310.—Oscillogram of brush drop between the toe of a positive brush and the commutator of a synchronous converter. Time scale 1 cm. = about 0·005 sec.

in the vicinity of the neutral plane, we can expect that the variations of the potential difference between bars and the brush with which they are in contact will be much greater than those indicated in

Fig. 238. In practice, this is often found to be the case. Figs. 308, 309 and 310 are oscillograph records taken at the heel, middle and toe respectively, showing the difference of potential between these different parts of a positive brush and the commutator bars that pass under them. The curves are somewhat erratic in formation, because their amplitude partly depends upon the resistance of the brush contact and this varies from instant to instant, owing to the slight chattering of the brush. The machine had twelve slots per pole and four commutator bars per slot. The fourth bar of the slot produces much more effect in the oscillogram than the other three though the effect of the others is just visible here and there. The main peaks on the curve are produced by the breaking of the current between the toe of the brush and the fourth bar and the variations of potential difference referred to in Fig. 238, augmented by the tooth ripple. It will be seen from Fig. 310 that the potential difference between the toe of the brush and the bar under it varies from +2·4 to −0·3; this corresponds to an exceedingly wide range of current density under the brush at the point in question.

The presence of the widely varying voltage drops can be detected by readings taken on a D.C. voltmeter and an A.C. voltmeter, as described on page 286. If an oscillograph is available, more exact information will be forthcoming; the complex wave obtained generally contains one harmonic having the frequency of the slots, and another having the frequency of the commutator bars. In Figs. 308, 309 and 310 the frequency of the bars is barely visible. The slot frequency is very pronounced, because it is much more difficult to commutate the current from the last bar in a slot than it is to commutate the current from the preceding bars. If the commutating pole is not of the right strength, the current from the preceding bars is taken up easily by the succeeding bars, on account of the close magnetic coupling between all bars lying in the same slot. Thus, if the commutating pole is too weak, the preceding bars in the slot will pass on the uncommuted current to the succeeding bars; so that when the last bar arrives at the toe of the brush it has much more than its share of the current to reduce to zero, before the break occurs. When the break does occur, it is so sudden that a kick voltage is generated in all coils near the neutral zone. This kick voltage makes a momentary increase in the current passing from any bar, and this gives rise to a higher drop in potential under the brush. These sudden changes in the brush-drop form the chief features in the oscillograms. The pulsation of lower frequency visible in Figs. 308 and 310 is due to an effect described on page 389. The chattering of the brushes also causes great irregularities in the curves.

Cure for tooth ripples. Where the indications are such as to lead us to believe that the tooth ripple is causing trouble, assuming that

it is not possible to alter the armature the following method may be adopted for suppressing it.

(1) Bevel the poles (both main poles and commutating poles) with a deep bevel having the same width as the tooth pitch, and arrange the depth of the bevel so as to make the reluctance of the magnetic circuit as far as possible constant for all positions of the armature. An alternative to bevelling the poles is to cut off the horns on the skew, but this may lead to mechanical troubles.

(2) Cover the tips of the commutating poles with a thick copper plate $\frac{1}{8}''$ to $\frac{1}{4}''$, according to the size of the machine. The eddy-currents set up in this plate oppose the quick changes of flux distribution under the commutating poles. The covering of the pole-horns of the main poles with copper, as was at one time done by the Westinghouse Company in the case of rotary converters and alternators, also has the effect of suppressing the tooth ripples, but is much more expensive than the bevelling.

(3) Where poles are provided with compensating windings or dampers lying in slots, these slots should not have the same pitch as the slots of the armature. If they have, the tooth ripple may be very pronounced. The best way to cure it is to mount the poles so that the slots are skewed exactly one slot pitch. Another plan is to alter the spacing of alternate poles by half a slot pitch. This will, however, make an unsymmetrical field and may spoil the commutation.

Skewed slots. The skewing of the slots in the armature is by far the most effective method of suppressing tooth ripples, but this is in general possible only on a new machine. The skewing of the main poles and commutating poles is sometimes possible on a machine that has already been built, but would not be resorted to until it was found impossible to suppress the tooth ripples by suitable bevelling and the addition of copper dampers.

Too few slots per pole.

The disadvantage of having a small number of slots per pole is two-fold: in the first place it increases the amplitude of the ripples in the wave form, and in the second place it increases the number of commutator bars per slot; and therefore the variation of voltage under the brush discussed in connection with Fig. 238 is greater. A machine with a large number of slots per pole, and one commutator bar per slot, comes nearest to the ideal in the matter of commutation.

Bad spacing of bars.

Though this matter was referred to earlier in this chapter, when we were considering commutator construction, the effect it produces is really an electrical effect and should therefore be considered here.

We have seen (page 328) that the distribution of the current between brush-arms depends upon the position of the brushes with respect to the potential distribution curve. If the bars are correctly spaced this position will remain unaltered; but if they are incorrectly spaced the position will vary as the commutator revolves. Thus two brushes that are correctly adjusted with respect to the field form are virtually rocked backwards and forwards with respect to the potential curve as the commutator revolves. The brushes will in consequence take alternately more and less current. At those instants when the current is great the commutating pole strength may be too weak, and at those instants when the current is small the commutating pole strength may be too great: thus the brushes spark whatever the adjustment of the pole may be.

If the commutator has been graduated with punch marks, as described on page 331, it will be possible, by inspecting the position of each punch mark with respect to the mica segment adjacent to it, to see whether the bars are correctly spaced, and, if they are not, to see the extent of the error. The extent of the permissible error in bar spacing is dependent upon the voltage of the machine, the width of the brushes, the absence of tooth ripple, and the excellence of the machine in other matters such as have been dealt with above. Where the "voltage under the brush" (see page 326) is low, the contact resistance of the brushes may go a long way towards combating the effect due to considerable error in bar spacing. Where the "voltage under the brush" is high, and especially where there are tooth ripples of considerable magnitude, very small errors in bar spacing may make the difference between passable commutation and very bad commutation.

On a 500-volt machine having a brush pitch (measured along the commutator) of 10″ and having as good commutating conditions as are commonly met with in practice, a cumulative error of $\frac{1}{16}''$ in the bar spacing may be sufficient to spoil that perfection in commutation which the designer likes to see. A cumulative error of $\frac{1}{8}''$ will in general make the commutation bad. If we wish to ascertain the extent to which the bad spacing of the bars affects the current distribution during the rotation of the commutator, the best plan is to connect german-silver strips between the brush-arms and the conductors into which they feed, as shown in Fig. 287*a*, and then to take an oscillograph record of the voltage drop in the german-silver strips at full load. Fig. 311 is a reproduction of a record of this kind: it shows that the current in the brush-arms on which the record was made varied from 120 amperes to 320 amperes during a revolution of the commutator. It is obvious that no commutating pole adjustment could be suitable for a load on the brush varying over such wide limits.

If a plot is made of the errors in the bar spacing and this is compared with the wave form of the currents in the german-silver strip, it will be found very difficult to determine the relation between the two records, because the current in any particular brush-arm is a function of the current in all the other brush-arms of the same polarity. It will, however, be found that the fundamental frequency of the variations in the two records is the same, and that the current distribution curve repeats itself every time the commutator revolves.

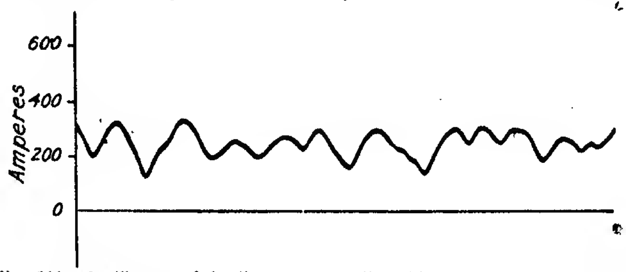


FIG. 311.—Oscillogram of the direct current collected by one brush-arm of a 10-pole synchronous converter, whose commutator bars were not evenly spaced. Time scale 1 cm. = about 0·005 sec.

The right cure for this cause of bad commutation is of course to space the commutator bars correctly. Where this cannot be done, the sparking may be considerably decreased by narrowing the brushes so that they do not short-circuit so many commutator bars, and by spacing them with great accuracy so that there are no small errors in brush spacing to be added to the errors in bar spacing. The use of a brush having a high contact resistance may be necessary in order to make the commutation passable.

Thickness of brushes.

On the ideal machine, free from tooth ripples and from voltage variation due to coil spacing, a thick brush would give easier commutation conditions than a thin brush, because the time taken to reverse the current would be greater and the voltage between bars under the brush would therefore be less. The total voltage under the brush would, however, be the same as for a thin brush. But the machines commonly met with are very far from being ideal; and the thicker the brushes are, the greater is the magnitude of the effects produced by tooth ripples and space variation of voltage. In fact, so much trouble caused by these factors is met with that it is commonly found that a machine operates better with thin than with thick brushes, notwithstanding the fact that the commutation E.M.F. is much greater than with thick brushes.

No criticism should be made upon the thickness of the brushes on any machine until all the troubles mentioned in Chapter IX. under

the heading of "Collection" have been eliminated and the other causes of sparking considered in this Chapter under the heading of "Commutation" have been fully investigated. After these things have been done, it may be found good policy, in order to minimize the trouble arising from some defect in the design, to change the thickness of the brushes. In doing so, we must have regard to the current density, and not make it too high, or we shall reduce the stability of the current distribution between brush-arms. Moreover, we must not increase the commutating voltage between bars to an abnormal extent. We have known cases where defects in commutation could not be economically remedied in any other way than by narrowing the brushes. The current density and the commutating voltage have accordingly been worked up to quite high values and have yet given a passable result on test; but it has been found that with the errors in brush spacing that occurred after the machine had been put into service, a small thickness of brush was not in practice satisfactory, and that more fundamental changes, directed to curing the real cause of the trouble, were necessary. In case it is thought advisable to narrow a brush, the best thickness can only be determined by having regard to the pitch of the commutator bars and to any error that may occur in the spacing of the bars. Assuming in the first place that all the bars are correctly spaced, the object of the engineer in fixing the width of the brush would be to short-circuit the fewest possible number of armature coils, at the same time keeping the brush as wide as possible. Suppose that he wishes to short-circuit not more than 3 bars: then if the bar spacing is perfectly uniform and he can rely upon perfect brush spacing, he may make the width of the brush just short of the pitch of 3 bars. If the brush were made a small amount wider than the pitch of 3 bars, it would at times short-circuit 4 bars: so that for a very small reduction in current density the commutating conditions may be made very much more difficult. On the other hand, a reduction of the brush width to very much below the pitch of 3 bars does not give much advantage in commutating conditions until we arrive at a width equal to the pitch of 2 bars; and here the current density may be very much greater than we care to adopt.

Returning to the case of the brush that must not short-circuit more than 3 bars, we must consider the possible error that may arise in the spacing of the brushes. Suppose that this is ·05″: then we must reduce the brush width to the pitch of 3 bars less ·05″. If, again, the spacing of the bars is not uniform and there is an error of ·05″ in the spacing, a further reduction must be made; so that the greatest permissible brush width will be the pitch of 3 bars minus 0·1″.

Bevelling of brushes. As a temporary measure for the purpose of experiment it is a good plan to bevel off the old brushes so as to make the surface in contact equal the new width that has been thought desirable. The machine may then be run under load conditions and the effect of the brush narrowing observed before new brush-holders and brushes are ordered. Sometimes it may be well to proceed step by step, making first quite a small bevel and gradually increasing it until the best results are obtained. In doing this, great care must be taken to see that the working facet of the brush is not disturbed in its contact with the commutator; otherwise the normal conditions of commutation will be disturbed. In bevelling brushes care must be taken to see that the spacing between the contact surfaces on different brush-arms is perfect, and that the brushes are rocked to the correct position.

In cases where the trouble does not arise from tooth ripples, space variation of voltage, or bad bar spacing, it may be found advisable to widen the brush so as to reduce the current density and the voltage between bars. A wide brush runs mechanically more smoothly than a narrow brush. It will generally be found that D.C. turbo-generators, that have been well enough designed to avoid tooth ripples and the other enemies of wide brushes, will operate much better with a wide brush. A considerable amount of air damping takes place between a well-fitted wide brush and the polished surface of the commutator and this causes an even pressure on the commutator such as cannot be so well obtained with a narrow brush. At the same time, there is a thin film of air between commutator and brush, which prevents the friction from being excessive.

Procedure in investigating collection and commutation troubles.

An inspection of the machine or our knowledge of the conditions may lead us to suspect a particular cause of the trouble. In that case, it may be well to direct our attention to the cause suspected, to shorten the investigation. But in default of any such obvious short cut, the following systematic procedure may be adopted.

Before starting the machine, make a cursory inspection of the brush gear; see that on the whole the brushes are feeding well, and that the brush-arms are somewhat near the correct running position.

Then run the machine on load and take a general view of the trouble complained of. Note whether the sparking occurs on all the brush-arms, and the amount of sparking on each arm. If some of the brush-arms show no sparking, we have evidence that it is not the "collection" that is mainly at fault. Probably the brush-arms are not correctly spaced.

Rock the brushes a little forward, and note the effect on the commutation. Take note especially whether the sparking is transferred

from one set of brush-arms to another. When this occurs, it is fairly strong evidence that the arms are not correctly spaced.

Then rock the brushes back a little way. This must be done with great caution, the ammeter being watched to see that the load does not increase too much or the machine become unstable. If the brushes are rocked back too far, the machine may attempt to take all the load and either flash over or bring out the breakers. The rocking forward and backward will enable the experimenter to determine the position at which the commutation is at its best.

It should be remembered that the mechanical disturbance of the brushes in their holders, or the tilting of the brush-arms, when the rocking gear is brought into play may have an effect upon the sparking, so that one must be careful to ascertain that the apparent change in the commutation is a permanent change due to the new position of the brushes on the potential curve, and not a mere accident due to the disturbance of the brushes. It is a good plan, when adjusting the brush-arms, always to finish off with a movement of the parts in the same direction: for instance, if the rocker ring is operated by means of a screw, it may be found that the bedding of the brushes is best if the screw has been turned clockwise. In that case the experimenter should finish off every adjustment of brush position by turning the screw clockwise. Make a special note whether the brush-rocker ring is firmly held or loose in its supports, and remedy any defect.

Having rocked the brushes to the best position, take roughly the voltage drop between commutator and brushes: this may be tried on several arms, and the values entered in a notebook, in which at the same time should be recorded the polarity of these brush-arms. If the brush-drop is taken at several points along the brush (see page 336), the readings will give some indication whether the commutating poles are much out of adjustment; but one would not at this stage take up too much time in carefully taking brush-drop curves, because the arms may be badly spaced.

Next take the voltage drop in the metal of the brush-arms themselves (see page 329), to see whether the current is divided equally between the arms.

If the voltage drop between the brush and the commutator for a normally loaded brush-arm is higher than it should be, having regard to the kind of brush employed, it is evidence that there is something wrong with the "collection" as distinguished from the "commutation."

The machine should then be stopped, and all the points mentioned on pages 296 to 318 should be closely looked into, in order to find the cause of the high voltage drop. If the mica has not been undercut or has not been sufficiently well undercut, the high brush-drop may be due to the mica's projecting by a microscopic amount above

the copper. Several cases have occurred within the author's experience in which one would ordinarily not have suspected high mica from an inspection of the commutator; but after the mica had been cut out the trouble was completely cured. In the same way, high and low bars the amount of whose projection or receding is so microscopic as to be invisible on inspection may cause the brush contact to have an abnormally high resistance. Where this is suspected, the commutator should be ground true. Where there is reason to suspect that the high brush-drop is due to chattering, we may adopt the temporary expedient of using a lubricant on the commutator to minimize the chattering, and ascertain whether for the time being the brush-drop is lower. If it is established that chattering is the cause, a rearrangement of the brush gear may be necessary, as discussed on pages 308 to 316.

After everything has been done to perfect the process of "collection" of the current, we can proceed to investigate the causes of bad commutation.

After the brush-arms have been correctly spaced (see page 331), a measurement should be made of the voltage drop in the brush-arms when running on load; and if the values at the various arms differ by more than 10 per cent. the cause of the discrepancy must be looked for (see page 333). Sometimes a small deficiency in the current taken by an arm may be corrected by adjusting the pressure of the brushes.

Where, after the brushes have been correctly spaced, the current collected by one of the brush-arms is consistently less than the average current per brush-arm, the cause of trouble may be either that the peak of the potential curve, Fig. 236, is distorted backwards or forwards by some dissymmetry in the arrangement of the parts, or that the peak of that curve is lower than it should be. In order to find out whether the peak of the potential curve is lower than it should be, the following plan may be adopted. An insulated brush, Fig. 291, is put into one of the carbon holders of the brush-arm in question (which we shall call brush-arm A), and another insulated brush is put into another brush-arm (B) of the same polarity. The second brush is then rocked to a point which measurement has shown to be at or near the peak of the potential curve. A voltmeter is connected between the two insulated brushes. If the two curves are of the same height, and if neither of them is distorted to the right or the left, there will be no reading on the voltmeter. If the deflection shows that the potential curve at B is higher than that at A, rock both brushes slightly forwards over a distance not exceeding 10 per cent. of the pole pitch, observing at the same time the reading of the voltmeter. If at any point the voltmeter reverses so as to indicate that the potential at A is higher than at B, we have

evidence that the potential curve is distorted; and a number of readings on the voltmeter will enable us to plot the difference between the ordinate of the A curve and that of the B curve. The brush holders should then be rocked backwards over a similar distance, and a plot should be made of the difference of potential. If these readings show that the A potential loop is not lower than the B loop on the whole, but that its maximum occurs at a different point, we must look for some dissymmetry in the field system, such as the bad spacing of pole pieces or unequal excitation of the commutating pole. It is well at this stage to make an examination of the commutating pole winding, in order to be sure that all commutating poles are of the correct polarity, and that the number of ampere-turns per pole is the same. If it should appear that any of these matters are not in order, they should be remedied. If, however, it is found that the peak of the potential curve at A is consistently lower than the peak of the curve at B, we have evidence that either one or both of the poles adjacent to A is weaker than it should be. Lap-wound armatures are generally provided with cross-connections between points of equal potential; so that small causes of difference in the strength of the pole do not show themselves on the potential curve, because their effect is wiped out by the equalizing current. Where, however, there is any very great cause of weakness, such as the complete short-circuiting or reversal of one of the shunt coils, or the reversal of a series coil, the equalizing current in the armature will not be able to bring up the loop of the potential curve to its normal height; and the presence of a short-circuit or a reversal of the field will be indicated by a test such as described above. It is a simple matter to find out whether the exciting coils are in order, and to see that the air-gap is the same under all the poles. The presence of bad blow-hole in the yoke may be detected by means of the magneto-potentiometer (see p. 192). On wave-wound armatures the weakness of one pole does not bring about an inequality in the height of the loops of the potential curve. It has the effect of lowering the voltage of the whole machine.

After we have made all adjustments to secure an equal distribution of current between the brush-arms, say within 10 per cent. we may proceed to adjust the strength of the commutating poles. For this purpose we take as a general guide our knowledge of the connection between the brush-drop curve and the rate of change of current, as explained on pages 338 to 341. In Figs. 292 to 297 the curves have been taken perfectly straight for the sake of simplicity; but very often brush-drop curves show considerable curvature. Where a brush-drop characteristic has a hump in the middle, it indicates that the rate of change of current in the coil is greatest as the coil passes the middle of the brush; this does not commonly

lead to commutation trouble. Where, however, there is a declivity in the brush-drop characteristic, we may have difficulty in adjusting the commutating pole so as to bring down the value of the voltage-drop at the toe of the brush. This kind of characteristic is obtained when the commutating pole is too narrow. It is as well to take the brush-drop characteristic on several positive and several negative brush-arms, and to compare them; if there are wide differences in the shapes of the characteristics, the cause of the difference must be investigated by taking the potential curve under each commutating pole, as described on page 282. It not uncommonly happens, on machines that are giving commutation trouble, that very bad sparking is apparent after the commutating poles have been adjusted so as to give what appears to be the best possible characteristic. In these cases, the brush-drop should be measured on a D.C. voltmeter and on a low-reading A.C. voltmeter. The difference between the squares of the readings gives the square of the value of the alternating voltage superimposed upon the D.C. voltage, see page 286. This gives us a measure of the effects mentioned on pages 352 to 360. In order further to investigate these effects, oscillograph records of the brush-drops at various positions along the brushes will be necessary. Where the alternating effect is due to a tooth ripple, the effect can be minimized by bevelling or skewing the pole tips, by shifting alternate poles circumferentially through a distance equal to half a slot pitch, or by covering the commutating pole shoe with a thick copper damper. Where the alternating effect is due to the grouping of too many coils in one slot, the effect can be minimized by half-stepping the coil, as described on page 342. This course involves the reconstruction of the armature. The bad effects arising from the fluctuating value of the brush-drop may be minimized by choosing a brush of the best width, as indicated on page 363.

Where the careful adjustment of the commutating poles fails to correct the sparking trouble, the spacing of the bars around the commutator should be checked, as indicated on page 360. If it is suspected that the trouble arises from the bad spacing of the bars, we may corroborate our suspicions by placing strips of german-silver between the brush-holder arms and the bus-rings, as indicated on page 329, and measuring the drop in these strips on a D.C. milli-voltmeter and on an A.C. millivoltmeter.* If an oscillograph is available, further corroboration of the disturbing effect of the bar-spacing upon the distribution of current between brush-arms will be forthcoming (see Fig. 311).

* The Cambridge and Paul Scientific Instrument Company make an A.C. millivoltmeter that is very suitable for this purpose.

CHAPTER XI.

DIRECT-CURRENT MOTORS.

SHUNT MOTORS.

Speed regulation.

When a shunt-wound D.C. armature is running as a motor, for a given polarity of the poles, it runs in the same direction as if it were a generator supplying power to the bus-bars. The E.M.F. generated by the armature is in the same direction as if it were a generator, but is smaller than the bus-bar voltage, instead of being greater. The current therefore flows against the generated E.M.F. and yields a torque in the direction of rotation: whereas if the machine were running as a generator the current would be in the direction of the generated E.M.F., and the torque would be against the direction of rotation.

The various effects considered under the headings of (*a*), (*b*), (*c*), (*d*) and (*e*) on page 248 come into play on a D.C. motor and influence the speed at which it runs.

(*a*) **Armature resistance.** As the current flows against the direction of the generated E.M.F., the IR drop in the armature must be subtracted from the bus-bar voltage; so that the effect of the resistance is to cause a drop in speed as the load increases.

(*b*) **Cross-magnetization and saturation of the teeth under the leading horn.** On a motor, the field is distorted against the direction of rotation and produces saturation of the teeth under the leading horn, which has the effect of decreasing the total flux per pole, as described on page 250. The reduction of the flux per pole makes it necessary for the motor to run at a higher speed in order to generate sufficient back E.M.F.; thus the effect of the saturation of the teeth is to give a tendency for the speed to rise as the load comes on. It will be seen from the curvature of curve (*b*), Fig. 235, that the tooth-saturation effect is very much more pronounced at higher loads. It therefore comes about that when (*a*) and (*b*) are operating together a small increase of load will sometimes cause a small diminution in

speed (owing to (*a*)); and as the load increases and the effect (*b*) predominates, a further increase in the load causes the speed to rise again. A very great increase of load may so weaken the field as to cause excessive current and bring out the circuit-breakers.

(*c*) **Rocking of brushes.** The effect of rocking the brushes on a D.C. motor is exactly the reverse of the effect on a generator. If the brushes are rocked forwards, the field is strengthened and the speed reduced; if the brushes are rocked backwards, the field is weakened and the speed increased. Curves c and c' in Fig. 235 represent quantitatively the effect that may be expected on the D.C. machine particulars of which are given on page 250. The rocking of the brushes is one of the most useful methods we have of controlling the stability of a shunt-wound motor. If owing to armature resistance the speed of the motor falls unduly as the load comes on, we may, by rocking the brushes a little backwards, improve the speed regulation. On most commercial motors, however, it will be found that the effect (*b*) out-balances the effect (*a*) on full load, and that it is necessary to rock the brushes a little forwards in order to keep up the strength of the field at heavy load.

(*d*) **Effect of commutating poles.** Where the brushes are on the neutral (see page 279) and the commutating pole is adjusted for symmetrical commutation, the commutating flux neither weakens nor strengthens the effective flux per pole. On a motor, the polarity of the commutating pole is opposed to the polarity of the main pole immediately ahead of it—that is to say, if we consider a conductor passing under a South commutating pole on a D.C. motor, the next main pole under which it will pass will be a North pole. It therefore follows that if we rock the brushes forwards the effect is to add some of the commutating-pole flux to the main-pole flux; and this will tend to give a decrease of speed on an increase of load. If, on the other hand, the brushes are rocked backwards, the commutating-pole flux is subtracted from the main-pole flux, and an increase of load tends to bring about an increase of speed. In this respect (*c*) and (*d*) operate in the same sense.

(*e*) **Effect of eddy-currents in the coils under commutation.** When a commutating coil is over-excited, so as to bring about a reversal of the current before the coil under commutation reaches the neutral point, the effect is the same as if the brushes had been rocked backwards—that is to say, an increase of load tends to bring about an increase of speed. When the commutating poles are under-excited, so that the reversal of the current occurs after the coil under commutation has passed the neutral point, the effect is the same as if the brushes had been rocked forwards—that is to say, an increase of load tends to cause a decrease of speed. The iron of the commutating pole will in some motors be saturated at heavy loads; so that

a motor that has its brushes on the neutral and its commutating pole over-excited at light loads has a tendency to keep its speed up during the first increase of the load. As the load increases and the pole saturates, the motor becomes more and more stable, and tends to drop in speed at heavy loads. This effect of the saturation of the commutating pole may be made to counteract to a certain extent the effect (*b*). The rocking of the brushes backwards and the over-excitation of the commutating poles can be made to neutralize the effect (*a*) at light loads; but it is not ordinarily possible on a commercial design to completely neutralize the effect (*b*) by this method.

Instability of motors.

The influences affecting the stability of a D.C. shunt motor are those considered under the last heading. Where the mechanical conditions are such that the motor can change its speed, it will run at such a speed as will enable it to generate such a back E.M.F. as, when subtracted from the available voltage of supply, will give a difference just sufficient to drive the load current through the armature. The motor thus becomes automatically stable through changing its speed to suit the resultant field excitation: the resultant field excitation depending upon the sum of all the effects (*b*), (*c*), (*d*) and (*e*) considered above and on page 218. If the sum of the effects is such as to reduce the field excitation to a low value, the load may rise to an abnormal amount, especially when the nature of the load is such (for instance, where the motor is driving a fan or a centrifugal pump) as to call for a very great increase of power when the speed is increased.

In investigating the cause of instability, we must have the effects (*b*), (*c*), (*d*) and (*e*) in view and endeavour to determine which of them is mainly responsible for the increase in the speed of the motor on load. The best procedure is to find the no-load neutral (page 279); rock the brushes forward of this point so as to entirely eliminate (*c*) and (*d*); and divert the current from the commutating pole to such an extent as to make certain that the effect (*e*) is not operative. If then the motor gains speed on load, the voltage in the bus-bars remaining constant, we may safely attribute the rise in speed to the effect (*b*). Where the motor drives a synchronous generator or in any other way is constrained to run at a constant speed, the effect of weakening the field is to increase the armature current, and this may in turn cause a still greater weakening of the field (see page 412).

The effect (*b*) can be minimized by increasing the air-gap under the pole, or—better still—by tilting the pole as shown in Fig. 242; but in the case of a motor the increased air-gap must come under the leading horn, instead of under the trailing horn as in a generator. The effect (*b*) can also be partly compensated for by rocking the

brushes forwards and by providing a commutating pole which saturates at full load and which at light loads is over-excited. It will be found, however, that on a machine with a very strong armature reaction and comparatively weak field-magnets it is practically impossible to maintain stability at heavy loads without the addition of a series winding. A method of improving the stability by means of a special exciter is described on page 413.

Shunt motors in parallel. Where several shunt-motors are running in parallel from the same mains, their stability greatly depends upon the mechanical conditions. If these are such that the motors can change their speed independently, then up to the limit of excessive loading considered in the last paragraph the motors become automatically stable. If, however, the conditions are such that the motors cannot change their speed independently, as where they are mounted on the same shaft or are driving synchronous generators, they will be unstable for all conditions of load in which the effects tending to weaken the back E.M.F. are greater than those tending to increase the back E.M.F. with load. The case of a D.C. motor driving a synchronous generator is dealt with on page 412; and what is said there is generally applicable to all D.C. motors running in parallel on the same bus-bars and constrained to run at exactly the same speed.

Hunting of shunt motor. It is sometimes found that when a motor is running on very weak excitation (for instance, when a variable-speed motor is running at its highest speed), the speed will not keep steady, but changes automatically, being first too high and then too low, through a cycle occupying several seconds. This action may be explained as follows: Owing to effects (*b*), (*c*), (*d*) or (*e*) (page 248), or to all four combined, the motor is unstable under the light field excitation, and accelerates. Part of the torque exerted by the armature is expended on acceleration, until a speed is reached at which the back E.M.F. becomes almost equal to the bus-bar voltage, and the current begins to decrease. The decrease in the current reduces effects (*b*), (*c*), (*d*) and (*e*), so that the field is strengthened. The inertia gained by the motor keeps it running at a speed sufficiently great, with the increased field strength, to generate a back E.M.F. that cuts down the armature current to a small value. The latter effect only lasts so long as the speed of the motor is kept up by its inertia. As the speed falls, the armature current increases; and, (*b*), (*c*), (*d*) and (*e*) coming into operation again, instability again sets in, and the motor begins to race.

If the hunting is mainly due to (*c*) and (*d*), it can be cured by rocking the brushes forward; if it is due to (*e*), the commutating poles should be diverted. When the effect is due to (*b*), it may be impossible to cure it for weak excitation of the field magnet without structural alterations to the motor.

COMPOUND-WOUND MOTORS.

The addition of a series winding, connected so as to co-operate with the shunt-winding and strengthen the field when load comes on, will always give greater stability to a motor. The effect is generally to cause a considerable drop in speed with load, and this may be an undesirable feature in some cases. If the series winding is not very strong, it may serve to give a slightly greater stability up to full load; but for very heavy loads the effect (*b*) (page 248) may become so pronounced that the speed may tend to rise notwithstanding the series winding. Instability may then set in and the armature current go on increasing until the circuit-breakers come out. The cure is to increase the strength of the series winding to such a point that for any prescribed load it is sufficient to counteract the (*b*) effect.

Compound-wound motors are sometimes built in which the series ampere-turns per pole at full load are in excess of the shunt ampere-turns Such motors have a speed characteristic resembling that of a series motor, and are suitable for cranes, haulage, and other work requiring a great starting torque. The shunt winding keeps the motor from running away when the load is taken off. If by accident a motor of this kind has had its small shunt winding connected in the wrong way, the mistake may pass unnoticed at starting or at heavy loads, because when the armature current is great it will overpower the shunt winding; but at lighter loads the motor will tend to run away. A good way to check the connections is to take the polarity of one of the poles with the shunt excitation only, and then again when a heavy current is passing in the armature. In the case of completely enclosed crane motors it is difficult to get at the internal poles. There is, however, sufficient drop of magnetic potential in the frame to make a slight field outside the motor, and the reversal of this field can be observed by means of a compass needle placed midway between the backs of two poles.

DIFFERENTIALLY-WOUND MOTORS.

A motor is sometimes provided with a weak series winding, which acts in opposition to the shunt winding, for the purpose of keeping up the speed of the motor as load comes on. Such motors tend to become very unstable at heavy loads. This is due to the increase of the (*b*) effect described on page 248. The field gets weaker and weaker with increase of load, and the armature current gets greater and greater, until the circuit-breaker comes out. A differentially-wound motor will never work well on heavy loads unless the armature

ampere-turns are low as compared with the field ampere-turns. A motor that tends to become unstable can be improved by tilting the poles, as shown in Fig. 242, the large air-gap being put on the leading side. This is only applicable to motors running in one direction.

Instead of providing a reversed series winding to make a motor keep up its speed on load, it is a much better plan to provide rather wide brushes and fit the motor with commutating poles whose cross-section is somewhat scanty, so that they saturate at heavy loads. If the commutating poles are excited so as to be rather too strong at any prescribed load at which it is desired to maintain the speed, the eddy-currents in the brushes can be made to weaken the field-magnet just enough to keep up the full speed at the prescribed load. At heavy loads the commutating poles will become saturated, so that the demagnetizing effect does not increase in proportion to the load, and the motor thus becomes much more stable than an ordinary differentially-wound motor.

SERIES-WOUND MOTORS.

Series-wound motors have a speed characteristic that drops quickly as the load comes on. They are mainly used for work in which the speed can be under the control of an operator, who by means of a controller switches in more or less resistance to get what speed he wants. For this reason there is very seldom any complaint about any defect in the speed characteristic. Nevertheless a series motor may be a great defaulter in the matter of its speed control. If the frame is made of bad magnetic material and saturates at a much lower flux-density than was intended in the design, the motor will run at a higher speed than was intended for a given load; and in order to keep down the speed the attendant will always have more resistance in circuit than would be necessary with a motor not so highly saturated. This is a serious defect, because it causes more current to be drawn from the line than is necessary to do the work, and may very much increase the annual bill for electric power.

Before a series motor is installed, very great care should be taken to ascertain the speed at which it is desired to run it when taking its average load. The motor should then be designed for that speed, and a test should be made to see that the speed is right at the average load when there is no resistance in circuit. Where sufficient care is not taken, a motor may be wasting power for years, though the attendant never notices that there is anything wrong.

Another defect that may pass unnoticed, unless special attention is given to it, is the short-circuiting of part of a field-coil. When the

wire of a series field-coil is insulated with cotton covering, it sometimes happens that the insulation becomes dry and brittle, and shakes off the wire, so that part of a coil becomes short-circuited. The only effect is to increase the speed of the motor for a given load; and as the attendant can bring the speed to what he likes on the controller, he fails to report any defect until the short-circuit of the coil becomes very much more severe.

CHAPTER XII.

SOME DEFECTS IN SYNCHRONOUS CONVERTERS.

Starting.

On A.C. side from taps on transformer. This method is very convenient, and is specially suitable for converters of small capacity. It saves the expense of a starting motor, and no synchronizing is required. For small converters up to (say) 100 kilowatts, having as much as 10 per cent. reactive drop in the transformer, one tapping will generally be sufficient, and this may be arranged to give about one-third normal voltage. For larger converters, two tappings are more commonly used, one at one-quarter normal voltage and the second at two-thirds normal voltage.

Several troubles may arise in connection with this method of starting. If only one tap is used and the voltage is arranged for one-third normal, so as to keep down the current drawn from the line on starting, then while the converter is running on the one-third tap the back E.M.F. is only one-third; and when the switch is thrown over to full voltage, we have an unbalanced pressure equal to two-thirds normal, which drives a rather great current through the converter during the short time required for the field to build up to full value. This may cause a momentary drop in the voltage of the system if its capacity is not great compared with the capacity of the converter. We may mitigate this trouble either by providing a second tap on the transformer (say at two-thirds voltage), or by providing choke-coils in series between the transformer and the converter, these coils being cut out after the excitation of the converter has been brought to full value.

When choke-coils are provided, it is better to have them in series with the higher-voltage taps rather than with the lower-voltage taps. The effect of the choke-coils is to limit the current drawn from the line, and if placed in series with the lowest starting tap they will limit the starting torque. It is better policy to choose the lowest tapping voltage that will give the requisite starting torque, rather than to put in a choke-coil, because by doing so we get the

full advantage of the better ratio of transformation between primary and secondary, and can thus draw a fairly large current on the low-tension side and a reasonable current on the high-tension side.

Another trouble arises in connection with the polarity of the converter when started up in this way. The converter starts as an induction motor, the dampers on the poles acting as a squirrel-cage. Some makers arrange a system of switches for opening the field-circuit at a number of points, so as to prevent the generation of too high a voltage by the transformer effect between the armature and the field-system. Other makers recommend the short-circuiting of the field-system during the first period of starting. One drawback to the latter plan is that the short-circuited field coils cause rather greater current to flow through the armature without giving a corresponding greater torque.

After the converter has almost come up to speed, so that the slip is very small, the shunt coils are connected to the terminals of the armature and are excited from the voltage on the commutator as it slowly changes from positive to negative. As soon as the slip is small enough to give either a positive or a negative excitation for a long enough period to enable the synchronizing torque to pull up the speed to full value, the machine comes into synchronism. It is thus a matter of chance whether any particular terminal of the converter will have positive or negative polarity. It is found in practice, however, that where the residual magnetism of the field-system is fairly great, the chances are on the whole in favour of the machine's coming in on the right polarity. When the polarity is wrong, the best way of changing it is for the operator to open the field-circuit and allow the converter to slip one pole. For this purpose he keeps his eye on the D.C. voltmeter. It will be found that as soon as the field-circuit is opened the voltage begins to fall to zero and then begins to build up in the opposite direction. The field-switch should then be quickly closed, and it will be found that the converter has just slipped one pole and that the polarity is now right.

To obtain the best starting torque with the smallest current taken from the line, the dampers on the pole should contain considerable resistance. The damper that is best for starting is not best for synchronous running on an unsteady frequency. In cases where the frequency is so uniform that no trouble is anticipated in the parallel running (as where the prime movers in the station are steam turbines), the dampers on the poles may be made of fairly high resistance, brass bars being used instead of copper bars; and a very good torque will be obtained with a comparatively small starting current. Where, however, the conditions are such that the dampers must be of very low resistance (see page 404), it will not be possible

to obtain a good starting torque without a heavy starting current. Sometimes ball bearings are used on converters, in order to make the starting current as small as possible; but these bearings are not recommended for large converters, unless they can be completely insulated from the pedestals (see page 133).

Self-synchronizing with starting motor and reactance. In order to keep down the starting current in large rotary converters, a small induction motor may be employed to bring up the machine to speed. The full voltage can then be thrown upon the slip-rings through choke-coils of very high reactance. As the starting motor is supplying the main driving torque, only a very small current need flow through the choke-coil in order to bring the converter into synchronism. The choke-coil gives the right phase to the synchronizing current, because it makes the phase position 90° behind the resulting E.M.F. (Fig. 104). For this purpose quite small and inexpensive choke-coils may be used, the coils being switched out of circuit as soon as the converter comes into step. The procedure is first of all to switch on the starting motor, and to close the starting switch, throwing the voltage on to the rings through the choke-coils. It will then be observed that the polarity on the commutator slowly pulsates. If now the field-switch is closed as the polarity comes up on a slow positive pulsation, the converter comes into step with the right polarity. Dr. E. Rosenberg proposed using the windings of the starting motor as choke-coils; and by the suitable design of the induction motor a very effective system of self-synchronizing was developed by the British Westinghouse Company. On this system, the collector rings are connected to the transformers through the stator windings of the induction motor, and as the converter comes up to speed these windings limit the synchronizing current; so that it is only necessary to choose the right instant for exciting the field-system in order to get the converter into synchronism with the right polarity.

The main troubles that arise in connection with this system are matters of design. The starting motor is made with one pair of poles less than the converter, and it is necessary to adjust the slip so as to give synchronous speed or nearly synchronous speed, with full voltage on the starting motor and normal excitation. While a certain amount of adjustment is permissible on the field-rheostat, it is sometimes found necessary to change the number of turns in the stator winding, in order to give the right turning moment at synchronous speed (see page 379 as to causes of excessive turning moment at synchronous speed).

Synchronizing with starting motor and synchroscope. Some engineers still prefer the old-fashioned method of starting a converter by means of an induction motor and a synchroscope. In cases where the frequency and voltage on the bus-bars are reasonably

steady, this method is quite as satisfactory as any other. Where the induction motor is made with one pair of poles less than the converter, the resistance of the squirrel-cage is adjusted so as to give approximately the right speed of the converter with full voltage on the induction motor. As it is not necessary to have the voltage on the slip-rings exactly the same as the voltage of the bus-bars before the A.C. switches are closed, the speed may be adjusted on the field-rheostat. An increase of the field-current increases the iron loss, and thus causes a greater slip on the induction motor.

Sometimes it is found that the rotary cannot be brought up to synchronism without reducing the excitation to a lower point than is advisable. The following are some of the causes that lead to this trouble:

(*a*) The brushes may have been rocked too far forward or too far backward. so as to cause very heavy eddy-current losses in them and the short-circuited coils. The cure is, of course, to rock the brushes to the neutral.

(*b*) The no-load losses on the converter are too high, owing to any of the causes that are mentioned in Chapter III., under the heading of Low Efficiency. The losses should be separated and any defects producing them remedied.

(*c*) The starting motor may be running from a lower tap on the transformer than was intended, or there may be some defect in the connection of the stator.

(*d*) The resistance of the rotor circuit may be too high. Sometimes bad connections have occurred between the bars and the end-rings of a squirrel-cage rotor, causing the slip to be too great. Some makers design the end-rings of the squirrel-cage rotor so that its resistance can be adjusted by making saw-cuts. This adjustment should be made before the machine leaves the works.

Starting from D.C. bus-bars. A rotary converter may be started up in the same manner as a D.C. motor, the starting resistance being put in circuit at first and gradually cut out as the converter comes up to speed. This method is suitable when D.C. power is always available on the bus-bars; or, where many converters are running in the same sub-station, one or two of them may be designed to start on the A.C. side and the others on the D.C. side. The speed of the converter is adjusted by means of the field-rheostat. The synchronizing may be done either on the low-tension side or on the high-tension side of the transformer. In the case of large converters, synchronizing on the high-tension side is preferable, because it avoids the use of large low-tension switches.

It may be that at the moment of synchronism the virtual value of the A.C. voltage of the rotary transformer is not the same as the A.C. voltage of the mains. If the A.C. switch were closed with the D.C.

circuit already made, the converter would immediately take load, the amount of which would depend upon the difference between the two voltages at the A.C. switches and upon the regulating quality of the converter. Under certain conditions this load might be excessive. *It is therefore usual, when starting a converter on the D.C. side, to open the D.C. circuit-breaker immediately before closing the A.C. switches.* Where the D.C. circuit-breaker is equipped with a trip coil, it is easy to arrange for the handle that closes the A.C. switch to make a contact that brings out the D.C. breaker just an instant before the A.C. switch closes.

At times when the frequency is very unsteady (as for instance after a general shut-down of the system, when the machines are just starting up again), there may be some difficulty in choosing the right instant for throwing a synchronous machine on to the bus-bars. For this reason, in all cases where it may be necessary to synchronize converters under very unsteady conditions, the plan of throwing the converter on to the bars through choke-coils is to be preferred, because the choke coils will prevent a heavy rush of current even if the switch is closed at exactly the wrong instant, and the synchronizing current that flows will pull the machine into step.

Voltage unsteady.

Sometimes rotary converters are run from A.C. mains on which the voltage is very unsteady owing to intermittent load or other cause. Any unsteadiness in the A.C. voltage will in general be reflected in the D.C. voltage. One cannot expect to get a steady D.C. supply under these conditions. If it is impossible to steady the A.C. voltage by installing a Tirrill or other regulator in connection with the A.C. generators, it will be possible to improve the conditions on the D.C. side of the converters by installing an A.C. booster between the converter and the transformer; this booster may have its field winding fed from an exciter adjusted by a Tirrill regulator that is under the control of the D.C. voltage. When the D.C. voltage falls, the Tirrill regulator increases the field excitation; and when the D.C. voltage rises the field excitation of the booster is decreased.

An unsteady D.C. voltage on the bus-bars of a shunt-wound converter may also arise from an intermittent load on the D.C. side, especially if the reactive drop in the transformer is excessive. The simplest cure is to put a series winding on the converter so as to level-compound it or slightly over-compound it.

Adjustment of D.C. voltage on rotary converters.

The methods that are employed for adjusting the D.C. voltage of rotary converters fall into two classes: (I.) those in which the A.C. voltage fed to the converter is adjusted; and (II.) those in

which the A.C. voltage fed to the converter remains constant and the D.C. voltage is adjusted independently.

Under Class I. fall five distinct methods.

(*a*) The A.C. voltage fed to the converter can be adjusted by changing the excitation of the A.C. generator supplying the converter. This can be done when the A.C. generator supplies nothing but the converter load, and when it is desired to change at the same time the voltage of all the converters connected to the generator: for instance, where turbo-generators and converters are put down for supplying direct current, it may be for electrolytic work. Here a very wide range of voltage variation may be obtained.

(*b*) The A.C. voltage fed to the converter can be adjusted by means of taps on the transformer. These taps may be either on the high-tension side or on the low-tension side. In the case of large transformers, they are usually put on the high-tension side, because the voltage per turn on the low-tension side is too high a percentage of the whole voltage.

The main trouble in this method lies in changing the connections from one tap to another when on load. Unless some special device is employed, we have a sudden jump in voltage as we pass from one tap to the next. Moreover, it is necessary to connect the next tap before disconnecting the last, and this will cause a short-circuit in the part of the transformer lying between the taps, unless a 'preventive' resistance or some other equivalent device is employed. Modern designs of controllers for connecting two successive taps and for the prevention of sparking have made this method more acceptable than in the past. One way of stopping sparking at the controller is to employ a small booster or induction regulator, and gradually boost the pressure derived from one tap until it reaches the same value as that of the next tap above. The connection can then be made without danger of short-circuiting, and it is possible to pass from tap to tap with a gradually increasing or decreasing voltage. For large installations, where the expense of such an arrangement is justified, the high efficiency of this method of changing the voltage has much to recommend it. It is possible to arrange the mechanism so that the whole range of voltage is obtained automatically by the mere turning of a handle.

Allied to the method of taps is the method employing a boosting transformer in series with the main transformer. This boosting transformer may have taps brought out from its primary, and these may be used in conjunction with a few taps brought out from the main transformer, so as to give a very wide voltage range with exceedingly small steps.*

* See *Journ. I.E.E.*, vol. 55, pp. 252 and 259.

(*c*) A third way of changing the A.C. voltage applied to a converter is by means of an induction regulator. This is built like an induction motor, with a rotor fixed to a shaft that can be slowly turned by means of a worm wheel, so as to change the angular position of the secondary coils with respect to the primary coils. *An induction regulator makes it possible for the voltage to be changed by infinitely small gradations, and eliminates all the difficulty of sparking on contacts. It is, however, more expensive than the tap* method, and not quite as efficient, because there are both iron and copper losses in the induction regulator. Moreover, the induction regulator is usually cooled by means of a fan driven by a small motor. The induction regulator is subject to many of the same troubles as an ordinary induction motor. The magnetizing current may be too great, owing to high reluctance in the magnetic circuit, or owing to misconnection of the windings. The windings on this kind of machine are often extremely complicated, and must be carried out strictly to diagram, which should be carefully checked by the designer, especially with regard to the polarity of ends of coils that are to be connected in parallel. All cases of trouble on induction regulators that have come within the experience of the author have arisen from misconnections in the primary or secondary windings.

(*d*) A fourth way of changing the voltage is by means of an A.C. booster mounted on the shaft of the converter. This is usually of the rotating-armature type, and is placed between the slip-rings and the armature of the converter. The stationary field-magnet may be mounted on the frame of the converter so that it can be rocked to any desired position with respect to the poles of the converter, or it may be permanently fixed. It is important that the poles of the booster shall have the right position * in this respect, in order that the machine shall give its maximum boosting effect.

Where an A.C. booster fails to yield its full boosting effect though fully excited, the trouble may be due to the fact that the field-frame is rocked to the wrong position. In cases when the frame is mounted in a manner that permits it to be rocked, the matter is easily remedied by moving it step by step and finding the point of maximum boost. It will be found that the point of maximum boost at no load is not the same as the point of maximum boost at full load. The maximum position is dependent somewhat on the power factor of the A.C. load.

In cases where the generated E.M.F. is greater than is required in service, we may rock the frame through an angle, so that the component of the booster voltage at right angles to the bus-bar voltage helps to improve the power factor. Other defects in the operation of this machine may be due to the troubles considered in Chapter VI.

* See *Specification and Design of Dynamo-Electric Machinery*, p. 547, for rule as to finding the right position.

(*e*) One of the most widely used ways of changing the A.C. voltage fed to a converter is by means of the reactive effect * of a leading or a lagging current in an inductance in series with the converter. Most commonly the transformer is built so as to have considerable magnetic leakage, and acts just as a choke-coil would in causing a drop in the voltage when the current lags, and a rise in the voltage when the current leads.

In choosing a particular voltage range on the D.C. side of the converter, we may have a large choice of possible arrangements: first, in the fixing of the no-load value of the voltage on the low-tension side of the transformer, and secondly in the choice of the amount of reactive drop to be allowed in the transformer when full-load current at zero power factor is flowing.

We may elect to fix the no-load voltage of the transformer at a value corresponding to the highest value of the D.C. voltage required at full load, allowing for the ohmic drop: so that an excitation of the field just sufficient to give unity power factor (on the low-tension side of the transformer) at full load will give the required voltage on the D.C. bars. To get a lower voltage, the excitation is reduced. This plan is suitable for over-compounded converters that are to be worked for long periods on full load, because it gives the least heating and the best efficiency. In cases where a range of voltage is required by means of shunt control at full load, it is better to fix the no-load voltage of the transformer at a point corresponding with the middle point of the range, over-excite the converter for the higher points of the range, and under-excite for the lower points. In cases where there are two definite points in the range at which the machine may be operated for long periods of time—as when a converter is intended to feed traction bus-bars at 550 volts and lighting bus-bars at 480 volts—the best plan is to arrange taps on the high-tension side of the transformer and change over the no-load value of low-tension voltage so as to get unity power factor at the most convenient point both on traction and on lighting.

After the no-load voltage is settled, we may elect to have a small reactance in the transformer, and a rather large lagging current, in order to get the required reactive drop; or we may elect to have a greater reactance in the transformer, in which case the lagging current required will be less. The relation between the amounts of lagging current required to give different ranges of reactive drop with different amounts of reactance in the transformer is given in Fig. 2 of a paper by Mr. Juhlin, Voltage Regulation of Rotary Converters (*Journ. Inst. Elec. Engnrs.*, vol. 55, p. 241). These curves do not take

* See *Specification and Design of Dynamo-Electric Machinery*, pp. 547 and 599; G. A. Juhlin, *Journ. Inst. Elec. Engineers*, vol. 55, p. 241; R. G. Jakeman, *The Electrician*, vol. 80, p. 191; also vol. 81, 22 Nov. 1918.

account of the saturation of the converter iron, and assume that the reactance is constant over the whole range. Fig. 5 in the same paper shows the effect of saturation of the reactive iron of the transformer. With a compound-wound converter in which the compounding is obtained by pulling down the voltage at no load by means of a lagging current, and in which the adjustments are made so as to get nearly unity power factor on the low-tension side at full load, there is a distinct advantage in saturating the reactive iron. When the iron is saturated, the inductance is not as great as it otherwise would be at full load. Thus we get the advantage of a high inductance at light loads, needing only a small lagging current to give the required inductive drop, without having the disadvantage of an excessively high reactive effect at full load, which would make too great an angle between the high-tension and the low-tension voltage. Suppose, for instance, that we decide to have not more than 25 per cent. reactive drop for full-load current lagging, and that this is obtained when the iron is saturated: the reactive drop for half-load current will be very much more than one-half of 25 per cent., because the iron will be less saturated at that load; and it will probably not take more than one-third of load current to make an inductive drop of 13 per cent. If the iron is not saturated and the reactive drop is proportional to the load current, it will take a lagging load equal to 52 per cent. of full load to make a reactive drop of 13 per cent. Thus for a given amount of reactive drop on full load, a converter working off a transformer with saturated reactive iron will require fewer series turns than one working off a transformer having unsaturated iron. This holds only when arrangements are such that the converter works at or near unity power factor at full load.

A knowledge of the facts stated above will go a long way to help in the curing of defects that may arise in connection with this method of voltage adjustment.

In Class II. the A.C. voltage supplied to the converter remains constant and the D.C. voltage is varied, (*a*) by changing the field-form of the converter or (*b*) by rocking the brushes.

(*a*) It has been proposed to change the ratio of transformation from A.C. to D.C. by changing the field-form of the converter. This can be done to a certain extent by splitting the pole into sections by planes parallel to the axis and independently exciting the sections so as to vary the field-form. Thus a change can be made in the ratio between the maximum voltage upon which the D.C. voltage depends and the virtual voltage on the slip-rings. The split-pole converter as actually constructed does not depend upon this principle. It depends upon the fact that by dividing each pole into two sections independently excited it is possible to *shift* the field-form relatively to the brushes. Thus we get a change in the D.C. voltage in very

much the same way as if we rocked the brushes relatively to the field. Thus if the two sections of the pole were equal and instead of being made both North poles one is made North and the other South, the whole field-form will be shifted through 90 electrical degrees, and the effect is the same as if the field had remained unaltered, but the brushes had been rocked through 90 electrical degrees. The result would be in both cases to reduce the D.C. voltage to zero although the A.C. voltage on the rings remained unaltered.

It is of course necessary to see that the changing of the excitation of the split-pole does not seriously interfere with the commutation. For this reason the brushes must be placed where they are in contact with coils which are passing one of the interspaces between poles, or under an inter-pole. Even then the machine will not be free from commutation trouble unless something is done to compensate for the changing armature reaction as the voltage is varied. On page 399 it is shown that the use of a booster to vary the voltage of a converter has the effect of varying the armature reaction, and as a consequence the inter-pole excitation must be varied by an amount which depends not only upon the load, but also upon the amount of the boosting. The same holds for a split-pole converter. For maximum D.C. voltage the A.C. armature reaction is co-axial with the D.C. armature reaction, but as the D.C. voltage is lowered the axis of the A.C. armature reaction becomes inclined to that of the D.C. and the inter-pole is weakened. This effect can be neutralized for any given load by means of shunt ampere-turns on the inter-pole. But the same sort of difficulty arises as that described on page 400. The same cures are also applicable in this case.

(*b*) Variation of the D.C. voltage by rocking the brushes. This method is very suitable where a range voltage adjustment of about 10 per cent. up and 10 per cent. down is needed and the conditions are such that the attendant has access to the brush rocker when he wishes to change the D.C. voltage. The converter must be specially designed so as to commutate well, with the brushes rocked over the whole required range. It is quite possible to design a converter in which the brushes can be rocked through 90 electrical degrees and work sparklessly at all loads up to full load. Such machines could be economically used to supply a variable voltage for starting up and running winding motors. They could also be used to supply a reversible voltage for running rolling-mill motors.

Heating of armature windings. When the power factor measured at the slip-rings is less than unity, the heating of the armature copper is considerably greater than when the power factor is unity. To make an exact statement of the way in which the heating depends upon the power factor, the number of phases, and other circumstances,

would take more room than we have available here. The reader referred to text books * and papers † upon the subject. The heatin of the copper ‡ of a synchronous converter is in general great nearer the points where the tappings are taken off to slip-rings tha at points midway between the tappings. When the current lag the winding near a tapping and immediately behind § it gets hotte than the part of the winding in front of the tapping. When th current is leading, it is the part of the winding immediately in fron of the tapping that gets hottest. It is the temperature of these hot spots that determines the load which a converter can take continuously at any given power factor.

If an armature of an over-compounded converter shows excessive *heating of the winding at points immediately in front of the tappings, after it has been running on a leading power factor, one of the first matters to enquire into is the possibility of getting the required* range of voltage by drawing a lagging current at light loads, so that the power factor may be near unity at full load. This can generally be done by changing tappings on the high-tension windings of the transformer to give 2 or 3 per cent. higher voltage at no load (unity power factor) than corresponds to the highest D.C. voltage required. Thus if a six-phase converter is required to be compounded between 510 volts no load and 550 full load, and the transformer is built for 25 per cent. reactive drop at full load, the transformer might be adjusted to give about 400 volts on to rings 1 and 4. This is arrived at as follows: 550+16=566; multiply this by the ratio between the D.C. volts and the volts on rings 1 and 4, say 0·7, and we get 400. In order that the reactive drop of 25 per cent. shall make no diminution in the secondary volts, the current will have to lead by about 7°, so that the power factor should be about 0·99 leading on the low-tension side. This is so near unity that it will not greatly affect

* Barr and Archibald, *The Design of Alternating Current Machinery* (Whittaker) 1913; *Specification and Design*, p. 541.

† Woodbridge, *Trans. Amer. I.E.E.*, vol. 27, p. 204; Juhlin, *Journ. Inst. Elec. Engnrs.*, vol. 55, p. 241.

‡ If m is the number of slip-rings, and α is the angular distance (measured in the direction of rotation) of any point P from the mid-point of a section of the winding lying between two tappings, and ϕ is the angle of lag of the current, the heating of the winding at the point P expressed as a fraction of the heating of a D.C. generator carrying the same load is:

$$1+\frac{8H_r^2}{m^2\sin^2\frac{\pi}{m}}-\frac{16H_r\cos(\alpha+\phi)}{\pi m\sin\frac{\pi}{m}}.$$

In this formula $H_r=\sqrt{h^2+k^2}$, where h is the ratio of the A.C. power to the D.C. power and k is the ratio of the wattless current to the power current at unity efficiency. Thus where 4 per cent. losses are supplied by the A.C. current, $h=1·04$, and where the wattless current is 0·26 of the working current ($\phi=15°$), then $k=0·26$.

§ A point is "behind" the tapping if it passes any fixed point on the field magnet after the tapping has passed it.

the heating. Resistance must then be put in the shunt-field circuit, so as to cut down the excitation and make the converter draw a lagging current at no load sufficient to pull down the voltage from 565 to 510. The series winding is then adjusted to more than compensate for the deficiency in the shunt ampere-turns at full load and to draw a leading current equal to 0·125 of the working current.

Low power factor. The lagging wattless K.V.A. will always be greater on the primary winding of the transformer than on the winding connected to the converter slip-rings. The difference between the wattless K.V.A.'s is made up of (*a*) the wattless K.V.A. required to magnetize the transformer and (*b*) the wattless K.V.A. brought about by the reactive drop in the transformer.

A transformer with a high inductive drop calls for a smaller lagging current to produce the required voltage drop, and a smaller leading current to give the required voltage rise; so that the power factor on the converter side is better when we have high reactance in the transformer. But it is difficult to get a leading power factor on the supply side of the transformer if the reactance has been chosen too high.

For any given voltage range there is a particular reactance drop at full load that gives the best results (see Fig. 2 in paper by G. A. Juhlin, referred to on page 383). In cases where the power factor is too low on the high-tension side of the transformer, a measurement of the no-load current should be made to see how far the magnetizing current is responsible. An enquiry should be made as to the reactive drop at full load; and if this is too high it may be possible to reduce it by changing the arrangement of the packets of reactive iron.

Two or more converters in parallel on the same transformer. Before the matter was properly understood attempts were made to run several converters in parallel, fed by the same transformer. Difficulty arises from the fact that a very large current may flow from the positive brushes of one machine, through the load and back to the transformers through the negative brushes of another machine. This may result in the overloading of one set of brushes, while those of opposite polarity are underloaded. The General Electric Company of Witton have devised a method* by which it is possible to run converters in parallel on the same transformer, the loads on the brush-holders being equalized by means of small differential choke-coils connected between the transformers and the rings.

* See *Electrician*, vol. 83, p. 492.

CHAPTER XIII.

SPARKING AT THE BRUSHES ON SYNCHRONOUS CONVERTERS.

ALL that has been said about the collection of current in Chapter IX. in connection with D.C. generators applies with equal force in the case of synchronous converters; and most of the troubles dealt with in Chapter X. in connection with D.C. generators may occur on any commutating machine. The only advantage that the rotary has over the D.C. generator in the matter of commutation is, that the excitation of the commutating poles need not include the large number of ampere-turns that are necessary in the case of a D.C. generator to counteract the armature ampere-turns. The number of ampere-turns on the commutating pole of a converter being substantially less than on a D.C. generator of the same output, the leakage flux from the commutating pole is generally less, and on that account saturation on heavy overload is not so liable to occur.

In some respects the commutating conditions on a rotary converter are more severe than on a D.C. generator.

Pulsating armature reaction.

It is well known * that the armature ampere-turns per pole on a three-phase full-pitch armature pulsate between the value of $\frac{0{\cdot}47 I_a Z_a}{\text{No. of poles}}$ and $\frac{0{\cdot}407 I_a Z_a}{\text{No. of poles}}$, where I_a is the virtual value of the alternating current per conductor, and Z_a is the total number of conductors on the armature. There are six pulsations per cycle.

Let us consider a 2-pole 6-phase converter supplying the current I_c at the D.C. voltage E. Then the D.C. power $= I_c E$. The alternating current per conductor in the armature, I_a, is equal to

$$I_a = \frac{\sqrt{2} I_c}{m \sin \frac{\pi}{m}} \times \frac{1}{\eta},$$

* *Specification and Design of Dynamo-Electric Machinery*, p. 270.

where m is the number of phases and η is the efficiency. In a six-phase machine $I_a = 0{\cdot}47 I_c/\eta$. The armature ampere-turns due to the alternating current therefore vary between

$$\frac{0{\cdot}47 \times 0{\cdot}47 \times I_c Z_a}{2\eta} \text{ and } \frac{0{\cdot}407 \times 0{\cdot}47 \times I_c Z_a}{2\eta}.$$

Taking η at 0·95, these expressions reduce to $0{\cdot}116\, I_c Z_a$ and $0{\cdot}101\, I_c Z_a$.

The direct current in the conductors is $\frac{I_c}{2}$, and the D.C. ampere-turns per pole are $0{\cdot}125 I_c Z_a$, without allowing for the fact that the conductors under the commutating pole do not carry full current. Making an allowance of 2 per cent. for this, we have the ampere-turns due to the direct current in the armature equal to $0{\cdot}1225 I_c Z_a$. Thus we see that the ampere-turns due to the direct current are always slightly greater than the A.C. ampere-turns; so that in addition to the ampere-turns required to yield the commutating flux, the converter under consideration should have on its commutating poles additional ampere-turns, the amount of which should vary between $\cdot 0065 I_c Z_a$ and $\cdot 0215 I_c Z_a$. If the commutating pole is excited by a steady direct current, one may take an intermediate value, say, $\cdot 014 I_c Z_a$, for the ampere-turns required in addition to those necessary to produce the commutating flux. The exact value will depend upon the efficiency.

Let the two-pole machine be yielding 200 kilowatts at 500 volts ($I_c = 400$), and let the total conductors on the armature be 192 in number. The ampere-turns due to the alternating current will vary between 7760 and 8920; while the ampere-turns due to the direct current will be 9417. Suppose the air-gap of the interpole is made rather short, so that the ampere-turns required to drive the commutating flux across it are only 2000. Let the excitation of the commutating pole be adjusted to give $2000 + 1077 = 3077$ ampere-turns, then the pulsations of the alternating ampere-turns of the armature will give us resultant effective ampere-turns on the air-gap varying between 1420 and 2580 ampere-turns: so that at one instant the excitation will be about 71 per cent. of what it ought to be, and at another instant it will be 29 per cent. more than it ought to be, and the commutation will be very far from perfect.

The effect of the pulsating M.M.F. of the armature in changing the strength of the commutating pole and thus changing the current distribution under the brushes is shown in Fig. 314. This figure gives an oscillogram of the brush drop taken at the toe of a brush of a 750 K.W. 50 cycle synchronous converter when running at full load.

The bigger lobes of the curve are produced by the pulsation of the armature. There are six of these lobes in one cycle of the supply

voltage. When the commutating pole is too strong, the current is driven to the heel of the brush, and the current density at the toe falls to zero, or perhaps reverses. When the commutating pole is too weak, the current is driven to the toe of the brush; and the current density is then so high that the brush drop rises to more than 2 volts. Superimposed upon the big lobes thus produced in the curve are a number

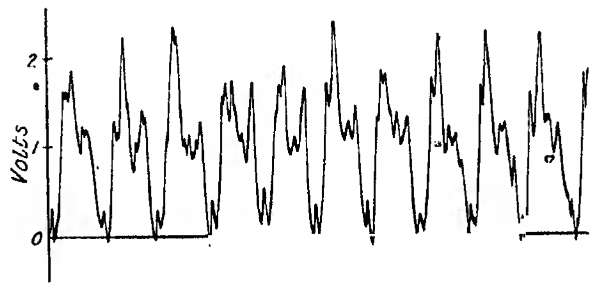


FIG. 314. Oscillogram of the brush-drop at the toe of a brush of a six-phase 50-cycle converter showing oscillation of current due to armature pulsating M.M.F. Time scale 1 cm. = 0·004 sec.

of irregular ripples, which have for the most part the frequency of the slots (there being 12 slots per pole). The frequency of the bars (48 per pole) is occasionally shown up by a minute ripple. The last bar in the slot, for the reasons mentioned on page 359, shows up much oftener than the others. The irregularity of the curves is due to irregularities in the construction of the commutator. The pulsation of the flux in the commutating pole can also be seen by taking

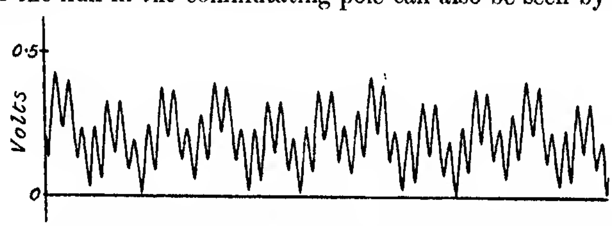


FIG. 315.—Oscillogram of voltage at the terminals of the commutating pole winding of a six-phase 50-cycle converter when on load. Time scale 1 cm. = 0·004 sec.

an oscillograph record of the voltage at the terminals of the commutating pole winding. Such a record is shown in Fig. 315. It shows up very clearly the sixth harmonic due to the armature reaction, and also the tooth ripple. There are exactly 24 of the little ripples in a complete cycle of the supply voltage. One cycle takes 0·02 second, which is represented by 5 cm. in Figs. 314 and 315. There are six of the bigger ripples per cycle. The mean value of the voltage at the terminals of the commutating pole winding was only 0·2 volts measured on a D.C. voltmeter. The pulsations take the voltage

up to ·43 and down to zero. The small ripples are mainly due to ripples in the armature current, which set up a reactive voltage at the terminals of the commutating-pole winding, acting as a choke-coil. The sixth harmonic ripple is partly due to the same cause, but is mainly due to the pulsation of the flux caused by the armature reaction. The ripple in the armature current was caused by a ripple very plainly seen in the oscillogram of the voltage between rings

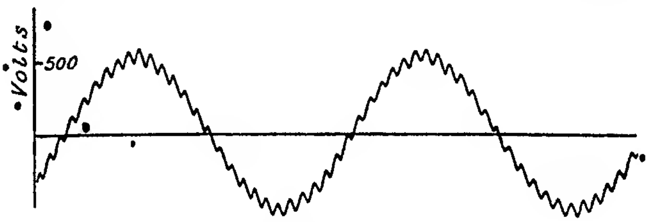


FIG. 316.—Wave-form of voltage in rings 1 and 4 of a converter with 12 slots per pole. Time scale 1 cm. = 0·004 sec.

1 and 4, shown in Fig. 316. This is not a simple tooth ripple caused by flux-swinging on the main pole, because its amplitude does not fall to zero when the voltage falls to zero. When the converter was on no-load, the E.M.F. showed a true tooth ripple, which fell to zero as the main wave crossed the zero line; but on load the superimposed ripple on the current and the effect of the teeth on the commutating pole gave the ripple a considerable amplitude even when the ordinates of the main wave were zero.

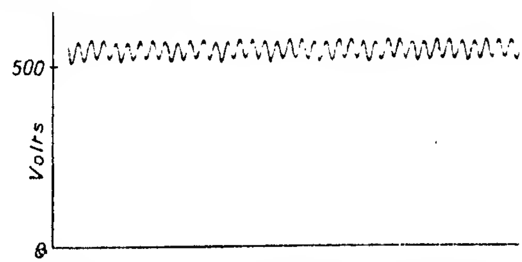


FIG. 317.—Oscillogram of voltage at the D.C. terminals of a six-phase converter showing tooth ripples and sixth-harmonic. Time scale 1 cm. = 0·004 sec.

This ripple was also very marked on the D.C. voltage. Fig. 317 gives the oscillogram of the D.C. voltage. Here in addition to the tooth ripples which have an amplitude of 20 volts, there is a slight wave having a frequency of 6×50. This is caused by the pulsation of the armature magneto-motive force. This sixth harmonic wave is more clearly seen in Fig. 318. When two synchronous converters are run back-to-back for the purpose of circulating the power on a

full-load run, the D.C. voltage contains the tooth ripples of both machines superimposed. One machine is running as an A.C. generator and the other as an A.C. motor, so that there is considerable phase difference between their generated E.M.F.'s; and as the tooth ripples are not sine waves their superimposition leads to a rather complex

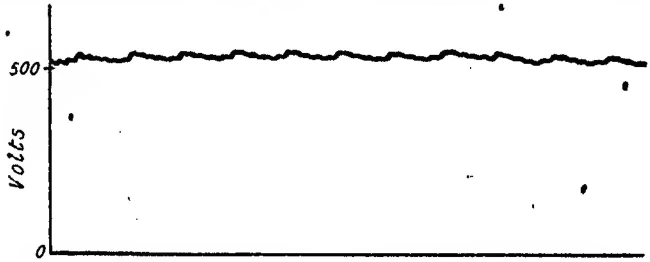


FIG. 318.—Oscillogram of voltage at the D.C. terminals of two six-phase converters running back-to-back and circulating full-load current. Time scale 1 cm. = 0·004 sec.

ripple, as seen in Fig. 318, which shows the oscillogram of the D.C. voltage taken under the conditions above described.

Under these conditions the direct current passing from one machine to the other may have quite a complex wave-form, with the sixth harmonic very pronounced. Fig. 319 shows the oscillogram of the direct current flowing between two synchronous converters connected back-to-back. It will be seen that the fundamental frequency can be detected, as well as the sixth harmonic, and a ripple

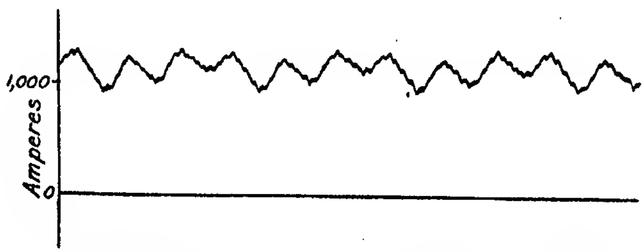


FIG. 319.—Oscillogram of direct current passing between two six-phase converters connected back-to-back showing sixth harmonic arising from armature pulsating M.M.F. Time scale 1 cm. = 0·004 sec.

having double the frequency of the teeth. The alternating current flowing between the two machines is also very complex in wave form, as will be seen from Fig. 327.

The pulsating reaction of a six-phase armature thus introduces a difficulty into the commutation problem of a synchronous converter, which is not present in the case of a D.C. generator.

Ways of combating the pulsation. One way of reducing the percentage variation of the commutating pole on a converter is to

make the air-gap of the commutating pole fairly great, so as to increase the resultant ampere-turns required to drive the commutating flux.

Increase of effective ampere-turns. Suppose that in the case given the air-gap were made sufficiently great to call for 6000 ampere-turns to drive the commutating flux across the air-gap, and that the excitation were adjusted to give $6000+1077=7077$ ampere-turns; the pulsation of the alternating ampere-turns would result in an effective excitation of 6580, or 10 per cent. too many, and 5420, or 10 per cent. too few, effective ampere-turns. If the total voltage under the brush (see page 326) did not exceed 20 volts, this variation of the effective ampere-turns would not lead to difficulty with the commutation. It will generally be found on modern synchronous converters that the ampere-turns on the commutating pole have been deliberately increased beyond what would ordinarily be thought necessary to create the commutating flux, the purpose in view being to reduce the percentage variation caused by the pulsating alternating-current M.M.F.

Dampers on commutating pole. Another way of counteracting the effect of the pulsating armature reaction is to provide each commutating pole with a damper of very low resistance. This may consist of a copper plate $\frac{1}{4}''$ thick covering the face of the pole,

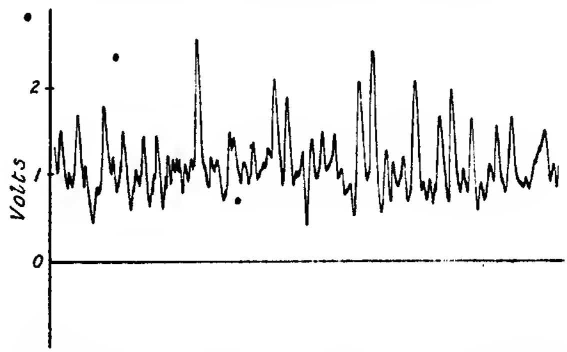


FIG. 320.—Oscillogram of brush drop taken under the toe of a brush of a six-phase converter with dampers on the commutating poles. Time scale 1 cm = 0·004 sec.

supplemented by a rectangle of copper encircling the pole shoe. If the resistance of this damper is made very small, it very effectually keeps the flux on the commutating poles fairly constant, notwithstanding the armature reaction: in fact, it acts like the secondary of a transformer and tends to wipe out the alternating ampere-turns.

The improvement effected in current distribution under the brush by the addition of dampers of this kind is illustrated in Fig. 320, which was taken under the toe of the same brush as Fig. 314, the load being the same in both cases. The damper almost entirely wiped out

the sixth harmonic; but it left unaltered the very big oscillations in the current density, which were due to other causes (see page 352). The commutation in this case was not improved by the addition of the dampers; but the elimination of the pulsation enables the experimenter to see more clearly that there are other factors in the problem.

Commutating field coils shunted by a diverter. Another way, which is just as effective and in some cases more convenient, is to make the number of turns on the commutating pole about twice as great as the number that would be required if the whole armature current went through them, and then to provide a diverter that diverts about one-half the current through a non-inductive resistance. It will be found that when the converter is on load the current through the commutating coil pulsates and keeps the resultant ampere-turns on the commutating pole fairly steady, notwithstanding the alternating armature reaction.

Armature short-chorded by one slot. It is common practice to short-chord the armature of a synchronous converter by one slot. Thus if there are 12 slots per pole, the coils are made to lie in slots 1 and 12, instead of in 1 and 13, as they would on a full-pitch armature. This has the effect of reducing the pulsation by about 40 per cent. Taking the same two-pole armature that we considered on page 389, and short-chording it by one slot, we shall find that the ampere-turns due to the alternating current will vary between 7800 and 8560, instead of between the wider range 7760 to 8920, and at the same time the D.C. armature ampere-turns are reduced from 9417 to 8900. If we arrange the interpole for an effective excitation of 6000 ampere-turns, and apply an extra 720 to overcome the armature mean M.M.F., we shall find that on full-load the excitation will vary between 5620 and 6380. This is only 6⅓ per cent. variation from the desired 6000 ampere-turns. If the winding were short-chorded by 2 slots (the coils lying in slots 1 and 11) the pulsation would be reduced almost to zero. It would be possible by suitable shaping of the main poles to make a converter commutate well notwithstanding the short-chording by 30 degrees. The corners of the main poles should be cut back so as to give a uniform field for the coils under commutation and the commutating coils should be made to embrace the main pole tips so as to provide a field of the right strength.

Twelve-phase converter. Another way of reducing the pulsations in the M.M.F. of the armature is to have 12 slip-rings and connect up the transformers to deliver the current in twelve symmetrical phases. In the case of large synchronous converters this does not involve such a great increase in complication as it might at first seem to do.

Six-phase converters of large current output have usually two or more cables to each slip-ring, to carry the current from the trans-

former. The change to 12 phases therefore makes no more complication in this respect. Further, the 12 rings of a 12-phase converter need only be one-half the size of rings on a 6-phase machine; and the total number of brushes will be the same in both cases.

There are many ways of transforming from 3-phase supply mains to a symmetrical 12-phase system. Where the transformers are already arranged to deliver 6-phase current, it is possible by the addition of three choke-coils, PP', QQ' and RR', connected as shown in Fig. 321, to obtain 12 phases. The secondaries of the main transformers are shown as AA', BB' and CC' connected in double star; but other connections are possible. Each choke-coil has two independent windings. Each winding has two taps, S and T, brought out, the voltage between each tap and the end being 0·268

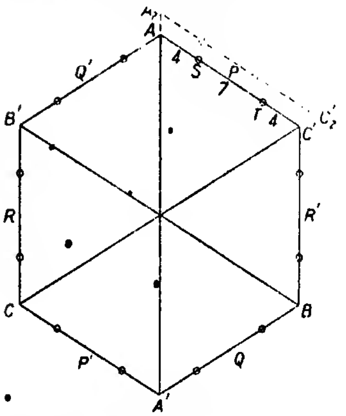


FIG. 321.—Arrangement of transformer in conjunction with choke-coils to deliver 12 symmetrical phases.

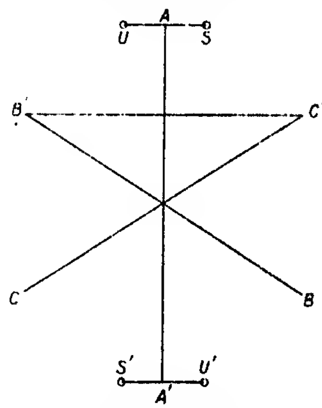


FIG. 322. Arrangement of main transformer in conjunction with auxiliary transformers to deliver 12 symmetrical phases.

of the whole voltage on the choke-coil. In practice, if each coil has 15 turns, it will be sufficiently near the theoretical value to bring out the taps four turns away from each end. These four turns must be of a section great enough to carry the slip-ring current; the remaining seven turns can be of smaller section. The ampere-turns of the two windings (P and P') on each coil can be arranged to wipe each other out, and the magnetic leakage made extremely small. The choke-coils, being worked at a low potential, need not be oil-immersed; their total K.V.A. capacity is about 0·27 of the main transformer. With the arrangement shown in Fig. 321, it is necessary that the ratio of the transformer shall be changed by about 10 per cent., in order to bring the points A and C' up to the point A_2 and C_2'. If this is not easily carried out by taps on the primaries, it may be necessary to adopt some other method of changing to 12-phase.

The arrangement shown in Fig. 322 is fairly simple. It involves the use of three auxiliary transformers, each with two secondaries. One transformer has its primary connected across $B'C'$, while the mid-points of the secondaries are connected to A and A'.

The correct ratio of this transformer is 6·40 to 2. This is so nearly 13 to 4, that if we have 13 turns between B' and C', we may have 2 turns for UA and two turns for AS. As before, the ampere-turns of US can be made to balance out the ampere-turns of $U'S'$, so that the wire required for the winding $B'C'$ may be quite small.

For the same load, the heating in a 6-phase converter is a little greater than in a 12-phase converter. At a power factor of 0·9, the rating from the heating point of view can be increased by 9 per cent. when the number of phases is changed from 6 to 12.

In general, however, the rating could be increased by more than this, because converters are seldom worked near to their heating limit, and the commutation on 20 per cent. overload of a 12-phase converter will be better than on a 6-phase machine at normal load.

Higher harmonic currents in the armature.

The alternating current that flows in the armature of a synchronous converter is driven by the difference between the E.M.F. supplied by the secondary of the transformer and the E.M.F. generated by the rotation of the conductors of the converter in the magnetic field. As in practice these E.M.F.'s are not of the same wave-form, the alternating current that flows is complex in its character and contains many pronounced higher harmonics.

When the secondaries of the transformers are connected in mesh and the three corners of the mesh are brought to the three rings of a three-phase converter, any third-harmonic E.M.F.'s within the windings are completely short-circuited within each mesh: and as the third-harmonic currents, and all harmonic currents whose order is a multiple of three, can flow without opposition, they wipe out by their reaction the irregularities in the magnetic field that produce them; so that the wave form of the E.M.F. on the rings is much nearer a sine-wave than it otherwise would be. Fig. 323 shows the wave form of the alternating current taken by a 750 K.W. 6-phase 550 volt synchronous converter, when connected up as a three-phase machine to the secondaries of transformers connected in mesh. The primaries of the transformers were connected in star to the primaries of another transformer similarly connected to another converter, by means of which the power was circulated, the two converters being connected on the D.C. side. The power to supply the losses was fed to the system on the A.C. side of the second converter. The oscillogram was taken when the machine was carrying a load of 350 K.W. The wave form did not change appreciably with the load. It will be seen

that with the mesh connection in the secondary the current taken by the converter is very nearly sinusoidal.

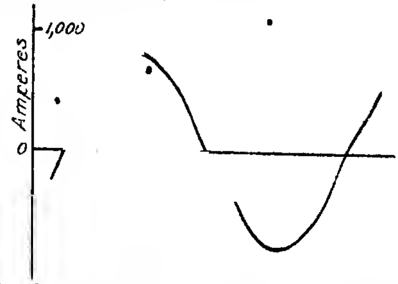


FIG. 323.—Wave-form of current fed to a 3-phase converter when the secondaries of the transformer were connected in mesh and the primaries in star.

Fig. 324 shows the wave form of the current with the secondaries connected in star, and with the primaries connected in star.

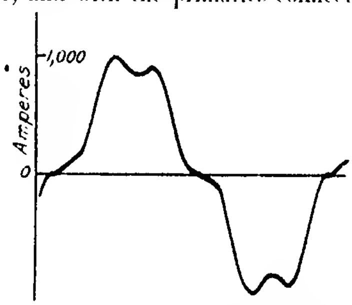


FIG. 324.—Wave-form of current fed to a 3-phase converter when the secondary was connected in star and the primary in star.

Fig. 325 shows the wave form of the current with the six-phase secondaries connected in double star, and the primaries connected in

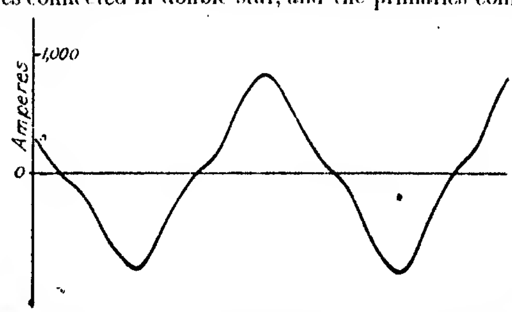


FIG. 325.—Wave-form of current fed to a 6-phase converter when the secondaries of the transformer were connected in double star and the primaries in mesh.

mesh. There the load on the converter was 750 K.W., giving about the same value of amperes per phase as with the three-phase connection.

Fig. 326 shows the wave form of the current with the six-phase secondaries connected in double star and the primaries connected in star, the load being 750 K.W.

It will be seen that the wave-form has pronounced harmonics.

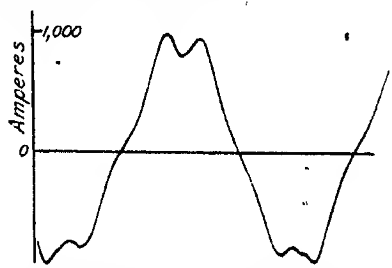


FIG. 326.—Wave-form of the current fed to a 6-phase converter when the secondaries of the transformer were connected in double star and the primaries in star.

The fact that the wave-form is not constant is probably due to a small amount of hunting between the two machines.

In one test on these machines the transformers were taken out altogether and the two converters run back-to-back, as six-phase machines. The alternating-current wave form (see Fig. 327), taken

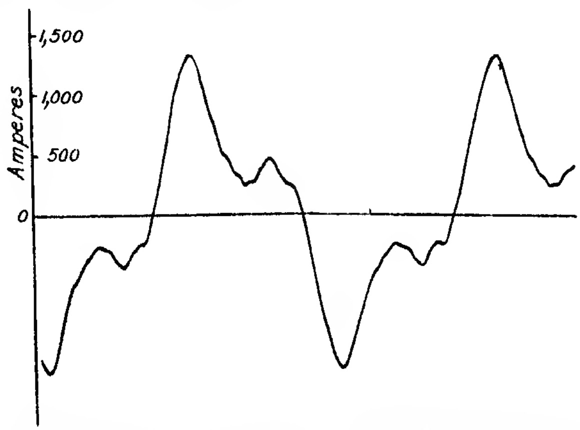


FIG. 327.—Wave-form of the current fed to the 6-phase converter connected back-to-back with another converter, no transformers being used.

at full load, shows a very great departure from the sinusoidal form: this is mainly due to the fact that one of the converters was over-excited and the other under-excited in order to make the power circulate. One of the armatures carried a leading current and the other a lagging current; and, the two field forms being different, very big harmonics flowed between the two machines in order to

equalize the E.M.F.'s. As all six phases were directly connected, there was no restriction to the flowing of the third harmonic.

It is generally found that the connection of the transformers with the secondaries in mesh gives the best conditions for commutation.

In the tests on which the above oscillograms were taken, this connection produced no noticeable improvement, because the main defect in the commutation was due to bad bar spacing (see page 300). The commutation when the machines were run back-to-back without transformers was not worse than when the transformers were connected to the converters in double star.

Saturation of reactive iron. In cases where a very large reactive drop in the transformer is required (see page 383), this drop is obtained by placing packets of laminated iron between the primary and secondary coils of the transformer. On heavy loads this iron may become saturated to a point well over the bend of the magnetization curve, and the shape of the magnetization curve introduces higher harmonics into the wave-form of the secondary voltage. This saturation effect has been known to cause a very serious interference with the commutating qualities of a synchronous converter. The cure is to break up the iron packets into short lengths, with air-gaps interposed every few inches of magnetic path, instead of having long packets and only one or two wide air-gaps. By increasing the cross-section of the packets, the same reluctance can be obtained as before; but the leakage flux increases more nearly in proportion to current.

One of the secondary effects of these higher harmonics is to set up in the coils under commutation E.M.F.'s of an exceedingly complex character; so that in addition to the load current in the brushes there are superimposed eddy-currents of various frequencies, the intensity of which at times is such as to lead to the generation of very much more heat than would be produced in a well-designed converter. Unfortunately, these higher harmonics are not under the control of the outside engineer who may be endeavouring to improve the performance of the converter. It is only by the suitable design of the alternator, transformer and converter that they can be reduced to very small dimensions.

The best way of reducing the deleterious effects of higher harmonics on commutation is to make the brushes as narrow as is compatible with reasonable current density. The use of a brush having a high contact resistance is also serviceable.

Effect of A.C. boosters on the commutation of synchronous converters.

A synchronous converter provided with an A.C. booster on the same shaft, for the purpose of adjusting the D.C. voltage, may be found to commutate badly, either when the booster is increasing or when it is decreasing the voltage. This action is easily under-

stood. When the booster is boosting up, it is driven by the converter which is then running as a synchronous motor. The extra A.C. power taken to drive the booster increases the A.C. ampere-turns on the rotary armature to a value higher than the figures given on page 389; and if the commutating pole has been adjusted on the assumption that the booster is not working, it will be too strong when the D.C. voltage is being boosted up. When it is boosting down the booster operates as a motor and communicates mechanical torque to the converter, which accordingly supplies a greater D.C. power than is represented by the A.C. power taken from the slip rings. This increases the D.C. ampere-turns on the armature and weakens the commutating poles; so that if the poles have been adjusted on the assumption that the booster is not in operation they will be too weak when the D.C. voltage is being boosted down. The amount of torque required to drive the booster when boosting up, and the amount of torque yielded by it when boosting down depend upon two factors: (1) the state of excitation of the field (2) the amount of the load.

In very liberally designed converters rated at not more than 60 to 80 kilowatts per pole, boosters having a range up to 7½ per cent up and 7½ per cent. down do not make any more disturbance in the commutation than can be met by the resistance of the brushes but in modern converters rated up to 150 kilowatts per pole or more and having boosters with a range of 10 to 15 per cent. up and down this action of the A.C. booster becomes very important, and must be taken care of by special devices.

Any devices that have in view the compensation of the action described above, by means of an auxiliary winding on the commutating pole, ought, strictly speaking, to take into account the two factors mentioned above.

Winding on commutating poles in series with the booster field. It is possible to put upon the commutating poles small coils connected in series with the field winding of the booster, so that when the latter is boosting up and the converter is running at full load the ampere-turns on the auxiliary coils will approximately counterbalance the additional A.C. reaction produced by the motor load on the converter. When the field-current of the booster is reversed so as to make the machine boost down, the current in the auxiliary coils is also reversed and will now strengthen the commutating poles and approximately compensate for the difference in A.C. armature reaction. There are, of course, certain losses in the A.C. booster that put a motor load on the converter whatever the direction of excitation; but the effect of these can in general be neglected. The device operates very well as long as the converter is run at approximately full load or near the load for which the auxiliary coils ha

been designed. On liberally-designed converters provided with boosters with a range of 10 per cent. up and down, this device has been found to operate well under practical conditions. The fact that it does not give perfect compensation at light loads does not lead to serious trouble.

Automatic control of commutating poles. Various devices have been suggested for automatically adjusting the commutating poles so as to roughly compensate for factors 1 and 2 mentioned above. Factor 1 can be taken care of by the method mentioned in the last paragraph; factor 2 can be allowed for by switching in and out diverters on the auxiliary winding, according to the amount of the lead.

Double-brush gear. The double-brush gear device described on page 351, when applied to a rotary converter, can within certain limits automatically compensate for the effect of the A.C. booster. When the commutating pole is too strong, the forward brush collects less current than the back brush and automatically weakens the field; if, on the other hand, the field is too weak owing to the D.C. voltage being boosted down, the forward brush takes more current and automatically strengthens the commutating poles. But the device cannot be relied on to correctly compensate for a wide range of boosting; because if we call upon the forward brush to collect a very much greater current than the back brush, it is obvious that the commutating pole cannot be the right strength for both brushes. The device is inexpensive, however, and works well up to the point where the current in the forward brush is about twice as great as the current in the back brush, or *vice versa*.

Unsymmetrical tappings.

In addition to the possibility of having an unsymmetrical A.C. winding such as is referred to on page 198, there is a possibility on a synchronous converter of having the tappings to the slip-rings taken out at unsymmetrical points. This not uncommonly happens in practice where the number of conductors on a series-wound armature is such as to make symmetrical tappings impossible. It may be that the deviation from symmetry is so small as to cause very little trouble in commutation. The outside engineer must be alive to the possibility of trouble arising from this cause, especially in machines designed several years ago. As a matter of principle, these unsymmetrical windings should be avoided by the designer.

Unsymmetrical windings.

It is important that the armature winding should be so designed that all points on the commutator having a distance apart equal to the distance between two positive brushes shall always be

at the same potential. This matter is dealt with very fully in the paper * by Dr. S. P. Smith on armature windings (see page 198). In cases where the number of slots per pole-pair is integral and where a lap winding is employed, points that are two pole-pitches apart are necessarily always at the same potential (assuming always a symmetrical field). In cases where the number of slots per pole-pair is not integral and where a wave winding is employed, very definite rules must be followed in order that the condition stated above shall hold. This, however, is a matter of design, and is only mentioned here to put the outside engineer on his guard against D.C. armatures in which the winding is not such as to give an equal potential at points where brushes of the same polarity bear.

Hunting of synchronous converters.

Another possible cause of sparking in synchronous converters may arise from a want of uniformity in the frequency of the supply. This cause will be intensified if the natural period of phase-swing (see page 228) of the converter is the same as the period of the disturbance in the frequency of supply.

The reason why phase-swinging causes sparking at the brushes is as follows: During the forward swing of the converter, power is supplied from the A.C. system and energy is stored in the rotating part as kinetic energy. The converter during the time it is gaining speed takes a greater motor load than it would if running steadily. During the backward swing the kinetic energy is being reconverted into electrical energy, and the converter in consequence carries a greater generator load than it would if running steadily. The motor load strengthens the commutating poles, and the generator load weakens them; so that we get over-commutation during the forward swing and under-commutation during the backward swing.

The extent of the swing of the converter depends mainly upon three factors: (1) the amplitude of the phase-swing of the supply system; (2) the amount of the magnification due to resonance; and (3) the efficiency of the damper. In order to deal intelligently with a defect in commutation arising from this cause it is necessary to understand exactly how these factors enter into the problem.

First consider the case of a two-pole synchronous motor running on a supply having a perfectly uniform frequency f. The voltage applied between a pair of terminals of the armatures would be represented by a vector rotating uniformly with the angular speed $2\pi f$ in a counter-clockwise direction. Now let us suppose that the frequency

* *Journ. I.E.E.*, vol. 55, p. 18 (1916).

is not uniform, and that the angular position of the rotating vector at any instant t is given by the expression

$$\theta_d = 2\pi ft - A \sin 2\pi f_d t,$$

where f_d is the frequency of the irregularity in the rotation of the vector, and A is the amplitude of the irregularity. Let us denote by γ the angular displacement of the vector from the position it would occupy if rotating uniformly. Then $\gamma = A \sin 2\pi f_d t$ measured in a clockwise direction. As on page 171, let σ represent the displacement of the centre line of a pole.

The angle γ is supposed to be measured behind * the vector which would represent the voltage if it were revolving uniformly.

The synchronizing force is then proportional to $(\sigma - \gamma)$, and the damping force is proportional to $(\dot\sigma - \dot\gamma)$. Employing the constants a, b and c with the same signification as on page 228, we get the equation of motion

$$a\ddot\sigma + b(\dot\sigma - \dot\gamma) + c(\sigma - \gamma) = 0,$$

from which we get

$$\sigma = -\frac{A\sqrt{c^2 + \omega^2 b^2}}{\sqrt{\omega^2 b^2 + k^2}} \sin\left(\omega t + e + \tan^{-1}\frac{\omega b}{k}\right), \quad \ldots\ldots\ldots\ldots\ldots(1)$$

where $e = \tan^{-1}\dfrac{\omega b}{c}$, $\omega = 2\pi f_d$ and $k = (a\omega^2 - c)$.

If $b = 0$, that is, if there is no damping, $\sigma = -\dfrac{Ac}{k}\sin \omega t$ and $k = a\omega^2(1-q)$, $\quad \sigma = -\dfrac{Aq}{1-q}\sin \omega t$, where $q = \dfrac{c}{a\omega^2}$.

That is to say, the original phase-swing of the supply is magnified by $\dfrac{q}{(1-q)}$ in the swinging of the revolving part of the motor. In the case where $q = 1$, σ will become infinite, if $b = 0$ (see page 230).

In the above we have taken a two-pole machine, in order that σ and γ, when measured on a simple clock diagram, may have the same magnitude as the displacements which they represent on the actual machine. If the converter has p pairs of poles, it is convenient to denote by α the actual angular displacement of the centre line of the poles behind the vector which represents the applied voltage of uniform frequency; and it must be remembered that in arriving at γ the amplitude A will be inversely proportional to the number of poles. Thus if A is the amplitude of the phase-swing of the

* For the sake of continuing the conventions adopted on page 228, we are considering here a synchronous motor having a revolving field-magnet. If we had (as is usual with synchronous converters) a stationary field and a rotating armature, the voltage vector would revolve with respect to the armature but would remain stationary with respect to the field system; and instead of using the word "behind" one should use the word "before" in relation to the movement of the rotating part.

voltage measured on a two-pole diagram, $A/p=A_p$ is the amplitude of the swing of the voltage vector on a machine of $2p$ poles.

Further, we have $p\alpha=\sigma$. Making these modifications in formula (1) on page 403, we get the same expression for the value of α as for σ, except that we take the coefficient A_p instead of A.

In the commutation problem we are interested to know how great the swing will be where $q=1$ and the damping is such as one might find in a synchronous converter.

Take the case of an 8-pole 1000 K.W. 50 cycle synchronous converter running at 750 R.P.M. The moment of inertia would be about 510 kilograms at a metre radius², so that

$$a=\frac{510}{9\cdot 81}=52\cdot 2.$$

If we have rather a poor damper, giving as much as 3 per cent. slip at full load when used as a squirrel-cage secondary, the value of the damping constant will be

$$b=\frac{10^6\times 4}{9\cdot 81\times 12\cdot 5\times 6\cdot 28\times 6\cdot 28\times 50\times 0\cdot 03}=5\cdot 5\times 10^2.$$

Owing to the high value of the armature ampere-turns, as compared with the field ampere-turns, the value of I_u/I_f (page 171) is usually low on synchronous converters. It may be taken * as 1·4.

We therefore get for the value of the restoring force,

$$c=\frac{10^6\times 1\cdot 4\times 4}{9\cdot 81\times 12\cdot 5\times 6\cdot 28}=7\cdot 28\times 10^3.$$

The frequency of disturbance that will give the worst resonance is found by writing

$$c=a\omega^2,$$

$$7\cdot 28\times 10^3=52\cdot 2\omega^2,$$

$$\omega=11\cdot 8=2\pi f_d.$$

Therefore $f_d=1\cdot 88$ cycles per second.

On the assumption that f_d has this value, so that $k=0$, we may proceed to calculate the value of the constants in formula (1) page 403.

$$\omega b=11\cdot 8\times 550=6\cdot 49\times 10^3,$$

$$c^2=7280\times 7280=5\cdot 31\times 10^7,$$

$$\frac{\sqrt{c^2+\omega^2 b^2}}{\omega b}=\frac{9\cdot 75\times 10^3}{6\cdot 49\times 10^3}=1\cdot 5;$$

$$\alpha=-1\cdot 5A_p\sin(\omega t+41^\circ\,44'+90^\circ)$$
$$=-1\cdot 5A_p\sin(\omega t-48^\circ\,16').$$

* See *Specification and Design of Dynamo-Electric Machinery*, pp. 342-345, or method of calculating the value of I_u/I_f.

The maximum value of $a\dot{a}=1{\cdot}09\times10^4A_p$ kilograms at a metre.
The maximum value of $b\dot{a}=550\times11{\cdot}8\times1{\cdot}5\times A_p=9{\cdot}75\times10^3A_p$.
The maximum value of $c\dot{a}=1{\cdot}09\times10^4A_p$.

The maximum value of the synchronizing torque is obtained by finding the maximum value of $c\,(\alpha-\gamma)$.

For this purpose we can set off the vector $c\gamma=7{\cdot}28\times10^3\times A_p$ as a horizontal line and the vector $c\alpha=1{\cdot}09\times10^4A_p$ lagging by the angle 48° 16′. The vector difference has then a length $8{\cdot}15\times10^3A_p$. The maximum value of

$$(\alpha-\gamma)=1{\cdot}12A_p.$$

Next let us see how great may be the amplitude of the phase-swing of the voltage.

Suppose that the A.C. supply comes from a 26-pole 3-phase generator driven by a gas-engine at 230 R.P.M. Let there be an irregularity in the speed, having a frequency of 115 per minute or 1·92 per second.

This will give almost exact resonance for some states of excitation of the converter.

If the flywheel of the generator permits of an angular irregularity in the speed of $\frac{1}{250}$th, we shall have a speed variation of $\cdot004\times3{\cdot}84\times2\pi$ radians per second ($3{\cdot}84\times2\pi$ radians per sec. being the speed of the engine).

This will give rise to an angular displacement of the voltage vector of $\dfrac{0{\cdot}004\times3{\cdot}84\times2\pi}{2\pi\times1{\cdot}92}=0{\cdot}008$ radian on the generator, or $0{\cdot}008\times\dfrac{26}{8}=0{\cdot}026$ radian on the converter.

So the maximum value of $\gamma=0{\cdot}026=A_p$.

But $(\alpha-\gamma)=1{\cdot}12\gamma$. Therefore the synchronizing torque under the worst conditions will be

$$c(\alpha-\gamma)=\frac{EI\times1{\cdot}4\times4}{9{\cdot}81\times R_{ps}\times2\pi}\times1{\cdot}12\times0{\cdot}026.$$

That is to say, the synchronizing torque may be about

$$1{\cdot}4\times4\times1{\cdot}12\times0{\cdot}026=0{\cdot}16$$

of full-load torque. This would very seriously affect the commutation.

If we make the damper of sufficient conductivity to reduce the slip to 1 per cent. at full load, we reduce the value of $(\alpha-\gamma)$ to $0{\cdot}374\gamma$, and the synchronizing torque then is only 0·055 of full-load torque.

The effect upon the commutation will depend upon the armature ampere-turns at full load and the ampere-turns upon the commutating pole.

Suppose that the mean A.C. ampere-turns per pole on the armature are 8000, and that the ampere-turns on the commutating pole are 6000. Taking 0·055 of 8000, we get 440 ampere turns added to the 6000 during the forward swing, and 440 ampere-turns subtracted during the backward swing. If the "voltage under the brush" (see page 326) is 20 volts, we should get 1·4 volts tending towards over-commutation on the forward swing and 1·4 volts tending towards under-commutation on the backward swing. If this were the only disturbance, the contact resistance of the carbon brushes would be sufficient to prevent bad sparking. It may happen, however, that the disturbance set up by the phase-swinging combines with other disturbances, such as those mentioned under other headings in this chapter, and that the combined effect is too great to be quenched by the carbon brush.

After what has been said above, it is clear that the cures for sparking set up by phase-swinging are:

(1) Minimize as far as possible the unsteady frequency in the supply. This matter is dealt with in Chapter VI.

(2) Arrange the constants a and c (page 228), of the converter so as to get as far away as possible from resonance with the phase-swing of the system. Theoretically, this might be done either (*a*) by changing the length of air-gap and hence the ampere-turns per pole of the converter, or (*b*) by changing the moment of inertia. In practice it is not convenient to change the moment of inertia; but the air-gap can in general be changed over a fairly wide range. A converter such as that considered on page 404 might have an air-gap anywhere between 2 mm. and 7 mm. long, if there is enough copper in the shunt coils to permit of the larger gap. If the ampere-turns on the armature teeth are not excessive, any change of the length of the gap through these limits will allow the value of the constant c to be adjusted so as to avoid resonance.

Sometimes there are two phase-swings of different frequencies in the supply voltage, and it may be difficult to get very far away from both of them. This may be especially difficult where the converter has to operate at various D.C. voltages, because the change in the excitation necessarily changes the value of c, and may for one of the excitations come dangerously near the resonance point. It is then necessary to rely somewhat upon the next expedient.

(3) Make the damper as effective as possible. For this purpose the copper damper bars should be fairly numerous and of as large cross-section * as possible. The joints with end connections should be well made and of low resistance. The end connections should be connected from pole to pole, so that the whole damper forms a sort

* The method of calculating the approximate slip to be expected with any given damper is given in *Specification and Design of Dynamo-Electric Machinery*, p. 352.

of squirrel-cage around the machine; though there may be necessarily some gaps in the spacing of the bars when the interpoles come.

SYNCHRONOUS CONVERTERS ON SHORT-CIRCUIT.

Synchronous converters are largely used for traction work; and it not uncommonly happens that a short-circuit occurs on the trolley line or third rail and leads to a very excessive overload on the converters feeding the line. When D.C. traction generators are subjected to overloads of this kind, they simply drop their voltage until the current falls to a reasonable amount; and as soon as the short circuit is removed they continue in operation as before. Synchronous converters do not as a rule behave so well. Their high efficiency and freedom from cross-magnetization on load enable them to maintain a high voltage on heavy overload; so that the short-circuit current becomes very much greater than it would be with D.C. generators of the same output. And this heavy current causes heavy flashing at the commutator. The arc may extend from positive to negative brush holder, and then nothing can prevent the bad burning of holders and commutator but the bringing out of the breakers on the A.C. side and the complete shut-down of the plant. Where a flash-over of this kind occurs, the commutator and brush-holders must be inspected and put into working order before the machine is started up and synchronized.

The main difference between the D.C. generator and the converter in this respect lies in the fact that the armature of a D.C. generator has a very heavy reaction, which upon a short-circuit can even overcome the series winding and almost instantaneously reduce the voltage to a very low value.

The converter, on the other hand, is provided with dampers on the poles, which prevent the sudden reduction of the magnetic flux when the short-circuit occurs. The flux being maintained for the moment at a high value, the armature yields a very heavy current, say from 15 to 20 times full-load value. In most cases the transformers are designed for a high inductive drop; and before the current has reached its maximum the voltage at the terminals of the transformers has fallen to a low value. The converter then behaves as an overloaded synchronous motor and goes out of step, in the meantime supplying the current to the D.C. system by virtue of its inertia. As it drops in speed, the magnetic field set up by the alternating currents in the armature, instead of being stationary with respect to the field system (as it is at synchronous speed), begins to revolve with respect to the frame and brushes; and violent eddy-currents are set up in the brushes as the armature's revolving field

Suppose that the mean A.C. ampere-turns per pole on the armature are 8000, and that the ampere-turns on the commutating pole are 6000. Taking 0·055 of 8000, we get 440 ampere turns added to the 6000 during the forward swing, and 440 ampere-turns subtracted during the backward swing. If the "voltage under the brush" (see page 326) is 20 volts, we should get 1·4 volts tending towards over-commutation on the forward swing and 1·4 volts tending towards under-commutation on the backward swing. If this were the only disturbance, the contact resistance of the carbon brushes would be sufficient to prevent bad sparking. It may happen, however, that the disturbance set up by the phase-swinging combine with other disturbances, such as those mentioned under other heading in this chapter, and that the combined effect is too great to be quenched by the carbon brush.

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Sometimes there are two phase-swings of different frequencies in the supply voltage, and it may be difficult to get very far away from both of them. This may be especially difficult where the converter has to operate at various D.C. voltages, because the change in the excitation necessarily changes the value of c, and may for one of the excitations come dangerously near the resonance point. It is then necessary to rely somewhat upon the next expedient.

(3) Make the damper as effective as possible. For this purpose the copper damper bars should be fairly numerous and of as large cross-section * as possible. The joints with end connections should be well made and of low resistance. The end connections should be connected from pole to pole, so that the whole damper forms a sort

* The method of calculating the approximate slip to be expected with any given damper is given in *Specification and Design of Dynamo-Electric Machinery*, p. 352.

quickly that they can catch the rising short-circuit current and break it before it reaches a dangerous value. Such breakers may be operated by a trip coil, which works only when the rate of change of the current reaches a prescribed limit.

(2) The second line of policy is to prevent the current from rising to too high a value by **short-circuiting the converter on the A.C. side** directly after a short circuit occurs on the D.C. side. Mr. N. W. Storer has described * several devices for carrying out this function. If three of the rings of a converter are short-circuited by means of contactors the instant after a short-circuit on the D.C. side occurs and before the direct current has time to do much injury, the voltage of the converter will suddenly fall to a low value and further arcing will be prevented. The short-circuiting of the rings brings out the A.C. breakers, and the plant must be restarted.

(3) The third policy is the most ideal. It aims at keeping the converter running synchronously, notwithstanding the fault on the system, so that it may resume its duties after the fault is removed without the necessity of restarting and synchronizing. Unfortunately, we have not yet gone quite far enough with the design of the converter and its adjuncts to make this policy completely successful. Many advances have been made, however, and there is hope that before long the ideal may be realized. In the first place, it has been shown that if the air on the face of the commutator and between the brush-holders can be changed rapidly and kept un-ionized, it is very difficult for the arc to jump between positive and negative brush-holders. Experiments made with 1500-volt converters provided with a strong draught of pure un-ionized air across the face of the commutator showed that short-circuits on the D.C. mains, though they caused very bad arcing under the brushes, failed to make a flash-over from brush to brush. The ionized air is produced by the passage of the current through the short air-space between the brushes and the commutator. A very strong draught of clean air is required to take it completely away. The next important step is so to design the converter and its adjuncts that the D.C. output on a short-circuit is not greater than the A.C. input from the transformer. If the damper on the poles of the converter is made to embrace only the trailing half of the pole face, and the leading half of the laminated pole is left without any encircling copper, any demagnetizing action can be made just as operative on the poles of a converter as on the poles of a D.C. generator. The weakening of the field-magnet in the event of a short-circuit can be accelerated by the use of a reversed series winding, shunted by a highly inductive shunt of very low resistance. The next step is so to adjust the drop in voltage of the converter that it almost corresponds to the drop in voltage of the

* See British Patent Nos. 120011, 124593; also F. C. Hanker, No. 128543.

transformer due to reactive drop. If this can be done successfully, the converter will run in synchronism notwithstanding the heavy drop of voltage. It will, in fact, operate as a converter designed for a lower voltage. *It is not necessary that the field of the converter should be reduced in exact proportion to the drop in voltage of the transformers. Theoretically, it is best to keep the excitation so high that the converter draws a leading current, but not so high as to approach the point of instability (see page 178). Again,* the adjustment of the commutating pole must be arranged so that under these heavy load conditions the commutating field-strength is sufficient to reverse the current under the brushes; and all ionized air must be removed from the commutator as soon as it is produced. The arrangement of the air-gap behind the commutating pole, as described on page 350, and the double-brush connection shown in Fig. 302, will be useful in keeping the commutating flux at the correct value. Finally, everything should be done that can be done in the way of keeping down the value of the short-circuit current and avoiding the breaking of a heavy current, as mentioned on page 408. By the combination of all these palliatives there is a reasonable prospect of making synchronous converters (even those delivering current at 1500 volts), withstand a short-circuit on the line as well as a traction generator can.

CHAPTER XIV.

OTHER DEFECTS IN SYNCHRONOUS CONVERTERS AND MOTOR GENERATORS.

Sharing of the load.

What has been said in Chapter VII., pages 243 to 275, and Chapter XI., pages 369 to 373, on the voltage regulation and the sharing of load between generators, applies with equal force in the case of motor generators; but there are some special problems that arise when motor-generators of various types are to be run in parallel.

Synchronous A.C. motor coupled to D.C. generator. A motor-generator set of this kind maintains a uniform speed at all loads, and is thus more liable to become unstable by the rocking backward of the brushes, or by the commutating winding being too strong, than a machine whose speed drops with the load. When the generator is connected in parallel with generators that drop their speed on load, care must be taken to rock the brushes sufficiently far forwards to prevent the synchronous set from taking most of any heavy rushes of overload that may come upon the combined plant: otherwise it may be found that on a momentary overload the synchronous set will break step and shut down.

Synchronous converters are also liable to take more than their share of overload when run in parallel with ordinary generators. Up to a certain point they can do this with impunity; but care must be taken when there are serious overloads on a station that too much of the peak is not thrown on to the willing horse. It is sometimes necessary to provide a converter with a reversed series winding when it is to run in parallel with a shunt generator, in order that its voltage characteristic may more nearly correspond with that of the generator.

Synchronous A.C. motor coupled to A.C. generator. Where a motor-generator set of this kind is installed, for the purpose of transferring power from one A.C. system to another, it is important that it shall be large enough to transfer enough power to keep the two systems running at the frequencies which correspond with the motor and the generator.

It is not possible to interconnect two large systems by means of a small synchronous set, because the speeds of the two systems are independently controlled, and the very smallest change in speed of one of the systems would take it out of synchronism with the motor-generator. Where the motor-generator is big enough for the purpose, the governors of the smaller system can be set so as to give a suitable load to their respective generators, the speed of the system being set by the motor-generator, which in turn has its speed fixed by the larger system.

When several motor-generators of this kind are run in parallel, they will, if exactly similar, take exactly the same load. The best way of adjusting the load between the sets is by having the stators of the generators mounted so that they can be rocked relatively to the stators of the motors. By rocking a stator backwards, we can adjust the load to the required amount. The power factor can then be controlled independently by varying the excitation.

Where the poles on the motor and generator differ in number, special provision must be made, when synchronizing the sets,* to see not only that an incoming set is in step with the bus-bars, but that certain marked poles are in step with certain marked poles of the sets already running.

D.C. motor coupled to A.C. generator in parallel with induction motor-generator and converter.

Some very interesting problems can arise in connection with a number of machines of this kind, that supply power to A.C. bus-bars in common. Consider first the D.C. to A.C. motor-generator. When it is connected to the A.C. bus-bars in parallel with other sets, its speed is fixed by the frequency of the A.C. supply. The amount of power delivered by the set depends upon the turning moment communicated by the D.C. motor to the A.C. generator. This again depends upon the current in the D.C. armature, and that depends upon the difference between the D.C. supply voltage and the back E.M.F. generated by the motor armature. In order to be stable, the motor must be given a speed characteristic that falls with load. If the adjustments are such that with increasing load the field becomes weaker and the back E.M.F. less, the motor will be unstable (see page 369). Referring to Fig. 235 and to what was said about the various effects (*a*), (*b*), (*c*), (*d*) and (*e*) on pages 248 to 267, it will be seen that the effect (*a*) always tends to stabilize the motor, and that effects (*c*) and (*d*) will help in the same direction if the brushes are rocked forwards. The effect (*e*) will also help if the commutating-pole adjustment is on the weak side. The effect (*b*), however, always tends towards instability.

* See R. Townend, *Journal I.E.E.*, vol. 55, p. 197 (1917).

It will be seen that the slope of curve (*b*) in Fig. 235 increases as the load increases; so that although the motor may be stabilized by effects (*a*), (*b*), (*c*), (*d*) and (*e*) at light loads, it may be found that after a certain load is reached the motor becomes unstable—that is to say, it takes more and more load and brings out the breakers. This difficulty is very much emphasized if the D.C. supply voltage is unsteady. The problem of making a number of machines of this kind share their load may be rather difficult.

In the first place, the D.C. motor designed for this work should have a fairly large air-gap and an unsaturated field-magnet. Its armature should not be too strong as compared with its field-magnet. Everything should be done to prevent super-saturation of the teeth at the highest loads contemplated. A tapering of the air-gap, as shown in Fig. 242 (the larger gap being in this case under the leading horn), will help a great deal in straightening the (*b*) curve (Fig. 235). When the D.C. supply voltage increases, it causes a corresponding increase in the field-current; and if it were true that the magnetic flux increased in the same proportion, the back E.M.F. of the motor would also increase in proportion, so that there would not be too great a difference between it and the supply voltage.

Unfortunately, the flux does not increase in proportion to the exciting current; so that a rise of 3 or 4 per cent. in the supply voltage may cause a very heavy current to flow through the armature, and, the effect (*b*) setting in, the motor becomes unstable and brings out the breakers. One way of overcoming the difficulty is to arrange for a small exciter to be driven by the motor-generator. This exciter should generate a voltage, V_e, equal to about half the supply voltage, and should have its frame magnetically saturated, so that its voltage is nearly proportional to its speed. The field coils of the motor-generator set should be arranged in series-parallel so as to require only about half the supply voltage. The exciter is then connected in series with the coils and the main supply voltage, V_m, in such a way that its voltage is opposed to the main supply and the coils receive a current that is proportional to the difference $V_m - V_e$. If now V_m increases by 1 per cent., the exciting current will increase by 2 per cent. It is not difficult to arrange the field-frame so that an increase of the field-current by 2 per cent. corresponds with an increase of the flux by 1 per cent. or thereabouts.

The back E.M.F. will then be more nearly proportional to the voltage V_m; and fluctuations in the supply will not lead to serious fluctuations in the load of the motor-generator.

Another advantage of the arrangement described is that it compensates in some measure for changes in the frequency of the system supplying the induction-motor-generator set. Without it, an increase in the frequency is accompanied by an increase in the

speed of the D.C. motor-generator set; and as the back E.M.F. becomes almost equal to V_m, the load on the motor falls to a low value, so that the induction-motor-generator set has to do nearly all the work. With the arrangement described, an increase of speed increases V_e, so that the difference $V_m - V_e$ becomes less, and more load is thrown on the D.C.-motor-generator set.

The induction-motor on the A.C. to A.C. set should be designed for a reasonably large slip, say 2 or 3 per cent., in order to make the conditions more stable.

The arrangement of the special exciter described also gives greater *stability of running in parallel with the synchronous converter, especially in the case when this is fed from a different D.C. supply* system. The converter should be supplied with a reversed series winding in order to give it stability.

Most complicated cases of parallel running between machines of different characteristics can be dealt with by means of automatic regulators of the Tirrill type, specially designed to meet the circumstances of the case. When this is done, it is most essential that the man who designs the regulator shall have a complete understanding of the characteristics of the various machines and the circumstances which cause them to be unstable.

Synchronous converters running from D.C. to A.C.

Sharing of the load. When running in parallel with other synchronous machinery, the speed is of course fixed by the frequency of the system. To make the power flow from the D.C. side to the A.C. side, it is usual to reduce the excitation a little below the excitation corresponding to full voltage at no-load. The lagging current drawn from the A.C. system tends to lower the D.C. voltage of the converter below the voltage of the D.C. system, and power flows from the D.C. system to equalize the voltage. If an A.C. booster or an induction regulator is employed, it is possible to vary the load without changing the excitation of the converter. Where there is a synchronous generator in parallel with the converter it is possible to vary the power factor of the load taken by the converter by varying the excitation. The higher the excitation the greater the lagging* current taken by the machine.

An ordinary steam-driven generator will not share the wattful load with a synchronous converter unless special precautions are taken to adjust the characteristics of the machines. The amount

* Note that as the converter is acting as a generator it is usual to take the direction of the current as positive when it is flowing along a conductor away from the converter, and a positive E.M.F. is taken in the same way. Thus a lagging current from this generator point of view is exactly the same as a leading current when the converter is regarded as a motor and the direction taken as *positive is reversed*.

of load upon the steam set depends only on the steam supply and this depends upon the setting of the governors. A synchronous converter with low resistance in its transformers and armature will maintain the voltage at the A.C. terminals fairly steady over wide ranges of load independently of its speed. When the load fluctuates the converter tends to take more than its share of the fluctuations, unless the resistance in circuit is adjusted to make the drop in voltage sufficient to keep the fluctuations down. Another way of stabilizing the converter in these circumstances is to provide an A.C. booster in series with the armature, and pass the direct current fed to the commutator through series field-coils on the booster, which is arranged to boost down in proportion to the load. By adjusting a diverter in parallel with the series coils the converter can be made to share wattful load in a reasonable manner for any given setting of the engine governor.

Unsteady frequency of A.C. side. If there is no synchronous generator in parallel with the converter, the frequency of the A.C. supply will depend upon the speed of the converter, and that again will depend upon the state of excitation of the converter. Let us suppose in the first case that only shunt coils are provided on the field-magnet; the machine then runs as a shunt motor, and what we have said on page 369 about the speed of shunt motors is applicable; but in addition to the various factors there considered which influence the speed, there is another important factor, namely the amount of wattless A.C. load.

When an A.C. generator is delivering a lagging current, that current weakens the field-magnet. As a synchronous converter running from D.C. to A.C. behaves on the A.C. side like an A.C. generator, any lagging current, such as magnetizing current supplied to induction motors, weakens the field-magnet and causes the speed of the converter to increase. An increase in the frequency of the circuit is accompanied by an increase in the self-induction effect of the circuit, so that the lagging component of the current becomes greater and the increase in speed greater: so that if there is no stabilizing influence a shunt-wound synchronous converter feeding a lagging A.C. load will tend to run away, and may attain a dangerous speed. For this reason it is well to install a speed-limiting device, which will automatically cut out the converter from the supply in the event of its attaining too high a speed. In addition, it is also usual to employ some stabilizing device which automatically keeps the speed nearly constant, notwithstanding the lagging load thrown on to the machine. One common form of stabilizing device is the following: A separate exciter is directly connected to the converter so as to run at the same speed; after the converter has been brought up to speed the armature of the exciter is connected in

parallel across the terminals of the exciting winding of the converter field-magnet, and then the connection with the D.C. bus-bars is broken, so that the machine runs as a separately-excited machine. The exciter is specially designed with an unsaturated field-magnet, and the resistance of its shunt coils is adjusted to the critical resistance, which brings the resistance line, Fig. 230, just a little below and almost coincident with the straight part of the magnetization curve (see the 100-ohm line in Fig. 230). In these circumstances the voltage of the exciter is extremely unstable: the smallest increase in speed makes the exciter build up its voltage to a high point, and a small decrease in speed makes it drop its voltage to a very low point. If now there is any tendency for the converter to increase its speed through the action of lagging current upon the armature, a small increase in speed causes a great increase in the exciting current, and thus the machine is stabilized.

Where in converters of this kind there arises trouble in speed-control, the following points should be looked to: The voltage across the armature of the exciter should be measured, to see whether its value agrees with the intended exciting voltage. Sometimes two rheostats are provided, one in circuit with the exciter shunt coils, and the other in circuit with the magnetizing coils of the converter. If the latter rheostat has been moved round to a point which calls for too high a voltage to be generated by the exciter, it may be that that machine is no longer on the unstable part of the magnetization curve, and is therefore unable to change its voltage through a sufficiently wide range when the converter changes its speed. It is well to run the exciter at various speeds from a little below normal to a little above normal, and to note how the volts change with the speed. If the machine has been properly designed for its purpose, one should expect to get at least 5 per cent. increase in voltage for 1 per cent. increase in speed. In taking this test, it is necessary to see that the brushes of the exciter are placed on the true no-load neutral; the rocking of the brushes forwards tends to stabilize the exciter. After the volt-speed curve has been taken and found satisfactory, it may be well to rock the brushes a little backwards to a point at which good commutation is still possible; the rocking backwards still further increases the instability of the voltage. If the magnetic circuit is unduly saturated at the lowest point at which it is possible to feed the exciting coil, it may be necessary to replace the exciter by one having a larger cross-section of iron in its magnetic circuit.

CHAPTER XV.

INDUCTION MOTORS.

Starting.

Squirrel-cage motors starting on reduced voltage. When the conditions are such that the motor can be started light, a squirrel-cage motor may be employed, started by means of taps taken from an auto-transformer, which supply to the terminals a lower voltage than the normal: the object being to keep down the current in the line at starting.* Sometimes a motor refuses to start because the voltage provided by the auto-transformer is too low to yield the requisite turning moment. For any given power factor in the rotor circuit, the torque exerted by an induction motor is proportional to the square of the voltage. A squirrel-cage motor designed for high efficiency and small slip will have a very low power factor at starting, because the value of the reactance of the secondary circuit, $2\pi f_s L_2$, is great as compared with R_2, the resistance of this circuit. This is because the frequency of the slip, denoted by f_s, is at starting equal to the frequency of supply. Even with full voltage applied to the stator winding, the torque may be only a small fraction of the full-load torque; and, when the voltage is reduced on the auto-transformer, the starting torque may be insufficient to overcome the initial friction. Suppose, for example, that the starting torque* at full voltage is 0·25 of full-load torque, and that the auto-transformer cuts down the voltage to one-third of full-load voltage. The starting torque will only be 0·028 of full-load torque, and this may be too small to overcome the initial friction.

It is necessary to enquire: (1) What is the value of the voltage at the terminals of the motor on starting? (2) Is the initial friction unnecessarily high?

(1) An A.C. voltmeter should be connected across the terminals of the motor, and the voltage should be observed when the starting switch is closed. It is well to check the voltages on all phases, in order to see that they are symmetrical. The pressure may be low, on account of voltage drops (*a*) in the supply system, (*b*) in the

* *Specification and Design of Dynamo-Electric Machinery*, p. 413.

auto-transformer. Usually it will be found that it is the auto transformer that is in fault, and that by changing to a higher tap *sufficient voltage can be obtained to start.*

(2) Where a motor has been standing for some time, and all the oil has run out of the bearings, the initial friction may be excessive. Barring round the motor once or twice will cure this. Sometimes the gear to be driven by the motor at starting is very much more difficult to drive than was anticipated, and the system of starting may be entirely unsuitable. An increase in the resistance of the rotor circuit by the use of high-resistance rings on the squirrel-cage, instead of copper rings, will improve the power factor of the secondary circuit and give the motor a better starting torque. These rings, however, will reduce the efficiency of the motor when running at full-load. In all cases when the starting torque is fairly heavy, induction motors of the slip-ring type or of the double-winding type should be installed.

Another cause of failure to start may lie in an open circuit, or a misconnection of some of the windings, see pages 36 and 198.

Star-delta starting. A motor designed to run at full voltage with its windings in delta may be started up with its windings connected in star. This has the effect of throwing only 58 per cent. of the full voltage across each phase. The starting torque is reduced to 34 per cent. of what it would be with the windings connected in delta and the starting current is reduced by 42 per cent. A failure to start may be due to: (1) insufficient voltage at the terminals; (2) the initial friction being unnecessarily high.

(1) The first step is to inspect the star-delta controller, to see that all connections and contacts are in order. It sometimes happens that the switch contacts of a controller do not make contact, although they appear to do so; and as the controller is generally immersed in oil it may not be possible to get a good view of the contacts under working conditions. It is a good plan to put an ampere-meter in the circuit of each phase, to see that the current is actually flowing, and to check the voltage across each phase.

(2) What is said under the last heading with regard to initial friction applies also to motors started on the star-delta system.

Slip-ring motors. In cases where the starting torque is considerable, it is usual to instal motors having wound rotors connected to slip-rings, so that resistances can be connected in series with the rotor at starting. Where a motor of this type refuses to start, it is a good plan to check the current in each of the roter circuits by means of an amperemeter: this shows definitely whether the circuits are complete, and whether they are reasonably balanced. If they are not complete, the circuits must be checked over by the methods already described in Chapters I. and III. All connections

should be thoroughly checked, to see that the current is flowing through the full resistance when the controller is on the first notch. The resistances should also be measured, to see that they are of the right amount.

The stator circuits should also be checked. Sometimes there is an open circuit in one of the phases, or one of the phases may be reversed, giving rise to an unsymmetrical field.

Excessive current at starting.

There are several causes that may lead to a motor taking an excessive current at starting.

Squirrel-cage motor switched in when running at full speed. A motor-generator consisting of a squirrel-cage induction motor direct-connected to a D.C. generator is commonly started on the D.C. side; and when running at full speed the stator winding of the induction motor is switched on to the mains. It is found in these cases that a very heavy instantaneous current flows through the stator winding; and unless the coils are mechanically very strong they may be injured by the great magnetic forces that come upon them.

Before the switch is closed there is no magnetic flux encircling the windings. When the switch is closed it is necessary for the flux to increase at a rate sufficient to generate a back E.M.F. almost equal to the voltage of supply. But this flux cannot grow in the rotor iron without setting up enormous currents in the rotor bars; and these call for enormous currents in the stator winding to neutralize them. Thus for the first instant after closing the switch the motor behaves as if it were on short-circuit, because although the rotor bars are moving at full speed there is no flux for them to cut. The flux at first grows along the leakage paths between the stator and rotor windings; and it is only as the heavy eddy-current in the rotor dies down that it takes up its normal position embracing both windings. The current in the stator follows a very complex law. Its value at any instant in any particular phase of the winding depends upon the position of the band of eddy-currents in the rotor with respect to that phase. This band of current is carried forward with the rotation of the rotor, and affects each phase in turn as it gradually dies down. If the rotor is not revolving at synchronous speed at the instant of short-circuit, there will be in addition to this current a torque current in phase with the flux.

Fig. 328 shows two oscillograms taken by Prof. E. W. Marchant on a 300 horse-power squirrel-cage induction motor coupled to a direct-current generator of 220 K.W. output. The motor was 3-phase, star wound, with 6000 volts between the lines. The frequency was 50, and the synchronous speed 428 R.P.M.

Before Fig. 328 (*b*) was taken, the rotor was brought up to synchronous speed by means of the D.C. generator running as a motor. The switch was closed when there was no slip. The oscillogram shows the voltage across phases A and C, and the current in phase B. The voltage V_{AC} is at right angles in phase to the voltage V_B. It will be seen from the diagram that the tall negative lobe of current is almost in phase with V_{AC} —that is to say, it is almost at 90° to the voltage V_B. This is what one would expect on an ordinary locked short-circuit test. The eddy-current in the rotor rapidly dies down, and the current then falls to its no-load value. The maximum value reached by the stator current was 380 amperes per phase, corresponding to an R.M.S. value of 270 amperes. As the full-load current is 26 amperes per phase, we see that under the above described conditions the current on switching in may rise to more than 10 times full-load current.

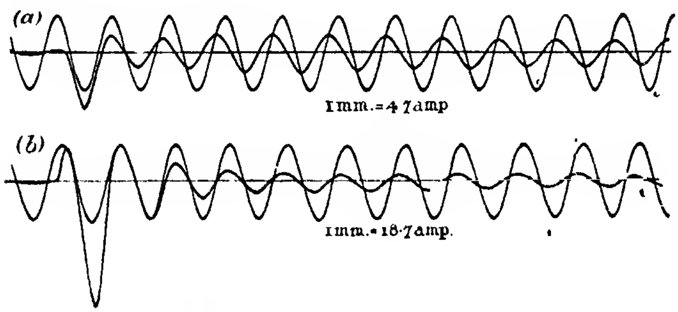

Fig. 328. Oscillograms of current taken by a squirrel-cage motor when switched on at full speed. (Prof. E. W. Marchant.)

In the case of Fig. 328 (*a*), no special care was taken to bring the speed exactly to synchronous speed. The current scale here is 1 mm. = 4·7 amperes, so that the maximum value of the current is, as before, about 380 amperes; but the time taken for the current to fall to normal value is longer.

The stresses upon the winding depend upon the maximum value of the current. This may be taken as a little below twice the maximum value of the current that the induction motor would take with the rotor locked and short-circuited. The current will be greatest if the switch is closed just after the voltage in one of the phases is zero. This allows an interval of time equal to half a period for the current to rise, so that it rises to almost double the value it would reach if the switch were closed when the voltage was at its maximum.

It may be that the winding is strong enough to resist the great rush of current without receiving any visible injury; but the repeated

shocks as the machine is started up day after day have an accumulative effect in distorting the winding and breaking the insulation. Cases have been known of induction motors running for several months as though they withstood the shock perfectly; and then within a short interval of time all the motors have broken down one after the other, the cause being the disintegration of the insulating tubes near the ends of the slots, or the insulation between turns.

One way of overcoming the trouble is to install a choke-coil between the main switch and the motor, and to arrange another switch to short-circuit the coil after the motor has been switched in. A choke-coil of quite small capacity will have very beneficial results. Thus a coil whose inductance is equal to the inductance of the motor windings on short-circuit will reduce the current to one-half and the mechanical forces to one-quarter.

Another trouble that sometimes arises when an induction motor is suddenly switched on to full voltage is the breaking down of insulation between turns. The turns of the coils nearest the terminals of the motor are especially liable to this trouble. Before the switch is closed an electrostatic field, due to the full pressure of the supply, exists between the contact surfaces of the switch. When the switch is closed, an electric wave is transmitted along the conductor; and the wave front may be so steep that the difference of potential between two conductors lying in the same slot may be much greater than the insulation between them can withstand. For this reason the coils near to the terminals of all high-voltage machines that may be subjected to electric waves arising from switching operations should be specially well insulated between turns.

Power factor of the rotor circuit too low. If the resistance of the rotor circuit is too low as compared with the reactance at starting the current in the rotor will lag so far behind the phase position of the flux as to yield very little torque even though the current may be excessive. If the rotor is of the squirrel-cage type it may be necessary to change the end rings for rings of smaller cross-section or rings made of metal of lower conductivity. Where the rotor is of the slip-ring type it is an easy matter to adjust the resistance to the value which gives the lowest stator current at starting.

Applied voltage too high. Any of the above mentioned causes of failure to start may lead to excessive starting current if the voltage applied to the stator is increased in an attempt to start without first curing the real cause of the trouble. If the voltage is increased two-fold, the torque will in general be increased four-fold, so that the motor may start notwithstanding a serious defect in its connections or adjustments. The starting current however may be twice as great

.s it should be, and as the power factor is low this may cause an undue lrop in the voltage of the system.

The taking of excessive current at starting may, of course, be lue to a misconnection or one of the defects in the windings conidered in Chapter III, and it may be necessary to completely test ut the windings by the methods there considered.

rawling of induction motors.

Sometimes a squirrel-cage motor after starting will crawl round at bout one-seventh of its normal speed and refuse to go any faster. 'his is due to a seventh harmonic in the field-form, which gives rise o a tooth-shaped projection on the torque-speed curve * as shown

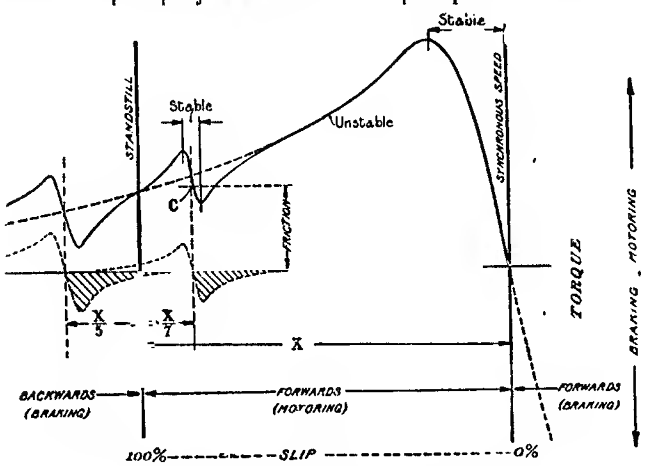

FIG. 329.—Speed-Torque curve of induction motor showing the tooth-shaped projections due to the fifth and seventh harmonics.

n Fig. 329. The seventh harmonic in the field-form makes to a ripple that travels forward at one seventh of the synchronous speed of the motor. The whole torque of the rotor is made up of the torque lue to the main revolving field plus the torque due to the seventh harmonic.

The torque is greatest when running slightly under synchronous speed. If we drive the motor above synchronous speed the torque becomes negative. Now the torque-speed curve of the seventh harmonic is of the same general shape as the main curve and crosses the zero-line at one-seventh of full speed, as shown by the dotted curve in Fig. 329. The fifth harmonic gives a ripple which moves

* See paper by Catterson Smith, *Journ. Inst. Elec. Engineers*, vol. 49, p. 635 (1912), in which the crawling of induction motors is very lucidly explained and from which the above figure is taken.

in the direction opposite to the main field. It gives rise to a negative torque, as shown by the dotted curve line to the left "stand still" line.

When the torques due to the fifth and seventh harmonics are superimposed upon that due to the fundamental wave we get the torque-speed curve shown by the full line in Fig. 329. We see that as the motor starts from rest the torque increases up to the little peak, and then rapidly diminishes as we approach what is the synchronous speed for the seventh harmonic. Above that speed the torque still diminishes, because so far as that harmonic is concerned we are getting a braking action. It is not until we have increased the speed by an amount which takes it well past the one-seventh speed that the torque again begins to increase. If now the friction of the motor should be such that it requires a torque greater than that supplied to the rotor in the region of the one-seventh speed, the motor will crawl round and be perfectly stable in maintaining its speed between certain limits.

If the motor is started from an auto-transformer it may be sufficient to change the starting tap so as to give a slightly higher voltage. If this cannot be done the difficulty may be got over by reducing the torque required at starting by some change in the gear to which it is attached; a very small change in the required torque may be sufficient to take the motor over the dip in the curve. Failing these expedients it may be necessary to make changes in the motor itself. The increase of the resistance of the end rings of the squirrel-cage will increase the starting torque. Rings are sometimes arranged so that raw cuts can be made in them to increase the resistance without weakening the mechanical support of the rings.

Where the stator of an induction motor is wound with a full-pitch three-phase winding, the field form has a pronounced seventh harmonic.

In cases where the winding lies in two layers, it may be a comparatively easy matter to short-chord it and reduce the seventh harmonic. The best amount of short-chording for this purpose is 30°. Thus, if there are 12 shots per pole the short-chording by two slots effects a very great improvement in the field form. The coils should lie in slots Nos. 1 and 11, instead of slots Nos. 1 and 13. If there are only 9 slots per pole the coils should lie in slots Nos. 1 and 8, 2 and 9, etc., in order to get a smooth field form.

Excessive slip.

Excessive resistance on the rotor circuit. On wound rotors provided with slip-rings the brush resistance is sometimes more than was intended by the designer and may lead to excessive slip. Motors intended to be run with the rings short-circuited should be provided

with a short-circuiting clutch inside the rings, so that the rotor current does not pass through the brushes except at starting. Where this is not supplied great care is needed in the bedding of the brushes and the adjustment of the holders to secure good contact between rings and brushes. Good graphite-metal brushes can be obtained on which the voltage drop is not more than 0·25 volt under actual service conditions, see page 307. If now the rotor winding is designed for voltage at starting as high as 400 per phase, the resistance of the brush will not increase the slip by 0·1 per cent. If, however, the voltage per phase is as low as 100 and owing to chattering and bad contact we are getting a drop in the brushes of 0·75, the slip will be increased by a corresponding amount.

In squirrel-cage motors the slip is sometimes increased by bad contact between the bars and the end rings. On wound rotors one of the phases of the rotor may be open either in the rotor itself or in the controller. Sometimes the slip is greater than expected because the load is greater than expected. If the voltage at the terminals is low the slip will be increased. This is especially the case in motors designed for a low pull-out torque.

Low power factor.

The power factor of a motor may be low on account of (1) the magnitude of the magnetizing current or (2) the excessive value of the magnetic leakage at full load.

If the current taken by the motor at no-load is measured and compared with the designer's data it will be seen whether it is necessary to search for some cause of excessive magnetizing current.

A possible cause is air-gap too great or unsymmetrical. This should be checked with feelers with the rotor turned through various angles up to 360°. Sometimes the rotor is slightly eccentric on the shaft. If the stator has been mounted so as to give an even air-gap all round with the rotor in one position the effect of the eccentricity will be doubled when the rotor is turned through 180°. As the rotor revolves the air-gap at two points, 180° apart, becomes alternately great and small. This sets up a demagnetizing eddy-current in the rotor and calls for a larger no-load current. Such a rotor should be taken out of the stator and an investigation should be made to determine the reason of the eccentricity. In small rotors which have their laminations pressed directly on the shaft, the eccentricity may be caused by the springing of the shaft, when the laminations were pressed home. In cases of this kind the shaft can be straightened by subjecting it to a judicious amount of bending in the right direction. On big rotors too, when the shaft has been bent by any accident it can usually be straightened without taking off the spider.

If the laminations are loose on the spider, they can be tightened

up by drilling holes between them and the spider and driving in keys. Judgment must be exercised in the arrangement of these keys in order to get the working face of the rotor concentric with the shaft and perfectly cylindrical.

When everything has been done that can be done in the way of straightening the shaft and keying the laminations and spider, if it is found that the surface of the rotor is still eccentric with the shaft, two alternatives are possible, (*a*) to grind the surface of the rotor, (*b*) to turn the journals concentric with the rotor surface. If the air-gap is already as great as is allowable, the second alternative may be the right one to choose although it will involve the re-babbitting of the bearings.

Another possible cause of excessive magnetizing current is the saturation of the magnetic circuit. This is a matter for the designer to deal with. All that the outside engineer can do is to satisfy himself that the correct voltage has been applied to the stator windings, and that these are free from short-circuits, open circuits, or reversed coils.

If the magnetizing current is normal and the low power factor is due to great magnetic leakage on load, this is again a matter for the designer.

It not uncommonly happens that the low power factor of the combined load of a number of induction motors in a factory is due to the fact that the motors are on the average much under-loaded.

When the amount of power required to run any machine is unknown there is a tendency to choose a motor a good deal too big for the work, and a number of these motors may bring down the average power factor of the factory. After the work to be done by each motor has been ascertained it will be possible to shift the motors around, giving bigger tasks to those lightly loaded and installing smaller motors where necessary.

Where big motors (say 300 H.P. or over) of the slip-ring type have been installed, and it is very important to improve the power factor, a phase-advancer * can be installed with advantage.

Pulling-out on load.

For every induction motor running with a given voltage across its terminals there is a maximum torque beyond which it cannot go. The maximum point of the torque-speed diagram (see Fig. 329) will occur at a point not very far below synchronous speed if the resistance is low, and at lower speeds as the resistance of the rotor circuit is increased. This maximum torque cannot be increased except by increasing the voltage or by the addition of auxiliary

* See *Specification and Design of Dynamo-Electric Machinery*, p. 605.

devices for advancing the phase of the rotor current. It is therefore important, when an induction motor is being installed for any particular duty, to see that the torque which the motor can exert will carry it through its work; for if at any time the load calls for a turning moment greater than the motor can yield, the motor will "pull out" and stop. The current taken from the line is then the short-circuit current on full voltage. This will bring out the circuit breaker and the motor will have to be restarted. As the turning moment is proportional to the square of the voltage, a drop in the line voltage may increase the liability of a motor to pull out if it is worked near its maximum torque.

Where inconvenience is caused through a motor occasionally pulling-out, the right cure is to instal a new motor with more suitable characteristics. Where this cannot be done, a rather good palliative is to arrange the switch gear so that the circuit-breaker operates upon a time limit, while another circuit-breaker inserts, in series with the rotor, resistances designed to limit the current drawn from the line and to enable the motor to start up under load. The motor then starts automatically as soon as the shock load goes off, and the attendant can throw in the rotor circuit-breakers as soon as it is up to speed.

The torque of an induction motor can be increased by cutting out some of the stator turns, but this should only be done on the advice of the designer.

Other troubles with induction motors.

The causes which may bring about a high temperature rise in induction motors and other machines were dealt with in Chapter II. Low efficiency was dealt with in Chapter III. In measuring the power taken by a polyphase induction motor, it is never safe to assume that the power on all phases is approximately balanced. A case occurred not long ago where a single-phase wattmeter was installed on one phase of a two-phase motor. After the motor had been installed for six months it was found that the meter gave a negative reading, showing that on the whole that phase had supplied power to the mains instead of taking power. It was then found that the phases were slightly unbalanced and that when the motor was running light (which was for the greater part of the day) one phase took power from the mains and the other phase, which contained the meter, yielded power to the mains.

Even when a polyphase wattmeter is employed, working upon the ordinary two wattmeter method (see page 158), the greatest care must be exercised in connecting it to potential transformers and series transformers to see that there is nothing in the way in which

these transformers are interconnected or earthed that will vitiate the argument upon which the two-wattmeter method is proved to be correct. A case came to the notice of the author in which a synchronous motor was supplied from a high-tension switchboard of standard design. There were two polyphase integrating wattmeters operated from potential transformers and series transformers in the ordinary way, and there was no reason to doubt the readings of the meters until it was found that when the motor was running light the meters went backwards. On full load the meters appeared to read correctly, and meter experts declared that the connections were all in order. As it was obvious that the motor could not supply power to the system, three single-phase meters were installed, one on each phase. These showed that the motor was taking its losses from the mains, as might be expected, although the polyphase meters continued to run backwards. The explanation appeared to be that a connection to a trip coil was made from the star point of the series transformers to earth, and this was sufficient to vitiate the statement (see page 160), that $i_a + i_b + i_c = 0$. Thus the chain of the argument upon which the validity of the two-wattmeter method is based was broken, and consequently two wattmeters were not sufficient to give a correct reading of the power.

CHAPTER XVI.

THE USE OF THE OSCILLOGRAPH IN COMMERCIAL TESTING

General requirements.

For the purpose of testing electrical machinery it is very desirable that the oscillograph outfit * used should be easily portable, convenient and expeditious in use, and adaptable to a wide range of voltage and current measurements. It is often necessary to measure three quantities at the same time, and for this purpose three vibrating elements should be provided each with its own field-magnet. Adequate amplitude should be obtainable on the oscillograms so that quantities may be measured off with a reasonable accuracy, and the photographic arrangements should be convenient. While many of these qualities can be obtained by a suitable arrangement of the circuits and accessories by the user, the first essential is to secure a suitable type of oscillograph. A good oscillograph of the Duddell type is made by the Cambridge and Paul Scientific Instrument Co. The General Electric Co. of America have developed the instrument and added some important features some of which are described below.

General Electric Co.'s oscillograph.

The oscillograph is of the Duddell type, the magnetic field being provided by electro-magnets. Three vibrating elements are provided, each with its own magnetic circuits. With the elements connected to their respective magnets, it is possible to work with 2500 volts between them, although this is seldom necessary.

The sensitivity of the elements with the standard strip is about 0·05 amp. per cm. deflection on the film. The natural frequency is about 5000 and small graduated spring balances are provided to facilitate ready adjustment of the strip tension. A great advantage is the facility with which an element may be replaced and repaired in case of accident. A spare element or vibrator can be inserted

* The subject matter of this chapter has been supplied by Mr. B. G. Churcher of the Research Department of the Metropolitan-Vickers Electrical Co. Ltd.

in about 5 minutes and a new strip and mirror put in the damaged element at leisure.

Photographic films $3\frac{7}{8}''$ wide by $12\frac{3}{4}''$ long are used. An amplitude of 4 cm. can thus be conveniently obtained. Six small metal drum cameras are provided which fit into a slot in the end of the box. These are connected to the driving arrangements by a small driving dog engaging in a slot. A special camera is also provided for use with extra long films. A very valuable feature is the electro-magnetic shutter, which exposes the film for exactly one revolution of the camera drum. The shutter can be released by hand or electrically, as will be explained later. The elements, optical system, electro-magnetic shutter and synchronous motor with tracing desk are all compactly arranged in one box.

General arrangement of oscillograph for works use.

In order that the oscillograph shall be very portable, it is fitted on a table with wheels, such as that shown in Fig. 330. A top and sides are provided so that the whole apparatus can be locked up. The back forms a convenient place for the fixing of switches, rheostats, etc. When it is required to test, for instance, a large generator, the truck is wheeled to a convenient position, the leads from the generator and from a 125 volt D.C. supply (for arc lamp and auxiliaries) are connected to terminals at the back of the truck and the oscillograph is ready for use.

On the back of the enclosure on the inside are mounted the following accessories: Main switch for 125 volt supply, arc lamp ammeter and rheostat. A short-circuiting switch is provided across a section of the arc lamp resistance, so that the intensity of the light can be increased just before taking a photographic record. A switch, ammeter and rheostat are provided for the synchronous motor which operates an oscillating mirror used for visual observation. A switch, ammeter and rheostat are provided for the electro-magnet of the oscillograph. The sensitivity of the elements is, of course, dependent on the magnet current, and it avoids trouble to always work with the same current. Adjustment of the camera speed, over a range of 600 R.P.M. (for 50 cycle work) down to 1 revolution in 6 seconds, can be obtained by means of the various pulley combinations, fine adjustment being obtained by a rheostat in the motor armature circuit.

The connections to the elements are arranged so that one element can be used for voltages from about 15 to 700, the second for voltages from about ·1 to ·15 and the third for the whole range, ·1 to 700 volts.

The adjustment of sensitivity is obtained by means of four rheostats fixed under the table at the front. The resistance units

in the rheostats are so proportioned that a 20 per cent. increase in amplitude per step is obtainable at any part of the range, so that a sufficiently gradual adjustment can be obtained over a large range of voltage with a moderate number of steps. The resistance of each step is known and tabulated so that the setting can be quickly made for a suitable amplitude at any voltage. If the quantity to be observed is periodic, the usual practice is to switch the element on with all resistance in circuit and turn the rheostat handle round until sufficient amplitude is obtained, as shown on the ground glass slide at the end of the oscillograph box. The use of rheostats in place of the conventional plug boxes has many advantages. The stepping is quite gradual and is easily adjusted, and the operator gets into the habit of returning the rheostat handle back to the "all in" position at the end of each test, thus cutting down the chances of damage to the elements by accidental excess current at the next test. With plug boxes the plugs are liable to get lost, the contacts cannot be readily cleaned, and the operator, when preoccupied with the details of the test, may easily put a plug in the wrong place and burn out the element. The adjustment of the amplitude with a plug box is necessarily tedious, as the operator must look alternately at the amplitude and the plug box to avoid accidents, whereas with a rheostat he can keep his attention on the amplitude. When using rheostats, it is necessary to ensure that the resistance units are sufficiently free from self-induction. In the rheostats shown in Fig. 330, the reactance at 1050 cycles is only 2 per cent. of the resistance, thus having a negligible effect on the amplitude of the twenty-first harmonic and a phase displacement of 11 degrees on that harmonic or half a degree relatively to the fundamental.

Current measurements are made by connecting the low-voltage elements across non-inductive shunts, which can easily be made up by the user according to his requirements. For high voltage A.C. measurements, shunt transformers are used. For large A.C. currents, series transformers are used, the secondaries being closed through suitable non-inductive shunts. With instrument transformers, the reproduction of wave form is sufficiently accurate for practical purposes, provided discrimination is used in selecting the transformers.

The oscillograph elements are calibrated by means of a battery and volt-ammeter of suitable range.

Some typical tests.

The recording of ordinary voltage and current wave-forms does not need any detailed description. A description of some of the less usual commercial tests may, however, be of interest.

Short-circuit tests on alternators.

The quantities usually recorded in these tests are the armature voltage, the armature short-circuit current and the field-current. The connections are made as shown in Fig. 331. The alternator is short-circuited by an electrically closed oil switch, the operating switch of which is placed on the oscillograph truck. To measure the short-circuit current, a bus-bar type series transformer is threaded on over one of the leads from the alternator to the oil switch, the secondary being closed through a non-inductive shunt, from which are taken leads to the oscillograph. A shunt transformer is connected as shown to obtain the armature voltage, and two leads are brought from a shunt in the alternator field-circuit to measure the field-

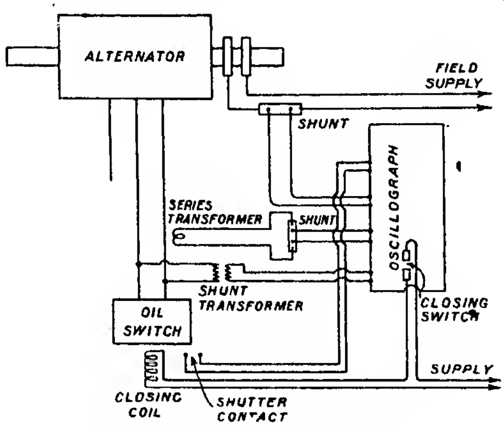

FIG. 331.—Connections between alternator and oscillograph for a short-circuit test.

current. An auxiliary contact on the oil switch, operated by an adjustable cam, is arranged to operate the electro-magnetic shutter on the camera, the timing being arranged so that the shutter opens just before the main contacts close. By this means, a few cycles of armature voltage wave are obtained before the machine is short-circuited, thus showing the instantaneous voltage at the moment of short-circuit. In taking a test, the rheostats in series with the vibrating elements are set to suitable positions (obtained by calculation from the anticipated short-circuit current), and the alternator run up to speed and excited. The film camera is then set running at a suitable speed and the arc lamp adjusted. Then when all is ready, the operator has only to throw in the closing switch and the test is carried out automatically.

It is usual, when the alternator is driven by a D.C. driving motor for test purposes in place of the turbine, to trip the circuit-breaker in the driving motor circuit just before the operator throws in the closing

switch. This avoids making the D.C. machine flash over due to an excessive rush of current from the supply mains. The inertia of large alternators is so great that the speed has not time to fall appreciably between the cutting off of the driving power and the application of the short-circuit. The advantage of an automatic arrangement such as that described compared with the usual hand-operated shutter is that it relieves the operator of all anxiety as to whether he will get a complete record of the test on the film, and thus he is enabled to use the length of film available to the best advantage.

Field-forms on machines. On a D.C. machine having a full-pitch winding, the field-form can be measured by taking tappings from two adjacent commutator bars and bringing them to the oscillograph through slip-rings temporarily fixed on the armature shaft. If a third ring is provided and tapped on to another commutator bar giving about 100 volts with one of the others, an alternating voltage is obtained from which the oscillograph's synchronous motor can be run, and the field-form at different loads and different excitations can be observed on the tracing desk. With a synchronous converter, a suitable synchronous voltage can be obtained from two of the A.C. rings. When using slip-rings, it is necessary to see that they run true, and it may be advisable to use several small brushes in parallel on each ring.

Voltage ripples on D.C. machines.

It is often necessary to examine the ripples in the voltage of

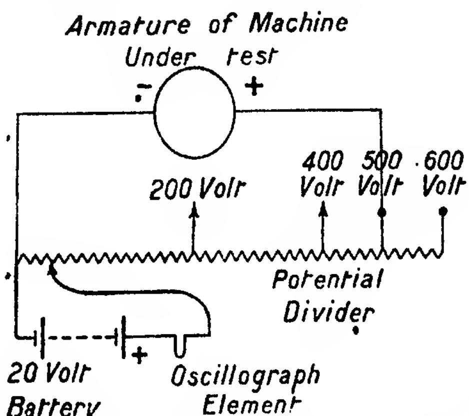

FIG. 332.—Arrangement of potential divider and battery for magnifying the amplitude of ripples.

D.C. machines or the D.C. voltage of rotary converters. The ripples are usually so small that they require considerable magnification to

enable the amplitude to be measured. The usual plan is to "back out" most of the D.C. voltage of the machine by means of a battery of approximately the same voltage. With low-voltage machines this method is quite satisfactory, but with a 500 volt machine a portable 500 volt battery would be very cumbersome and not at all necessary. The test can be conveniently carried out with a 20 volt battery on a machine of any voltage by using a potential divider such as that shown in Fig. 332. The potential divider consists of a number of non-inductive resistance units mounted on a stand, and can be seen on the right in Fig. 330. Tappings are provided so that about 2·5 amperes are obtained down the potential divider for a machine of any voltage. It is important that the self-inductions of the potential divider and the oscillograph circuits shall be negligibly small as compared with their resistances.

Let a be the amplitude in centimetres of the ripple on the curve above the mean deflection, A. Let s be the sensitivity of the oscillograph in volts per centimetre, V the mean voltage tapped off from the potential divider and e the battery voltage.

When no battery is used

$$As = V,$$

and the ratio $\frac{a}{A}$ may be very small.

When the battery voltage is opposed to V, we have $As = V - e$, and we may accordingly increase the value of s and make the height of a much greater. The magnification is then $V/(V-e)$, that is to say, to get the true ratio of the ripple in the voltage to the mean voltage we must take the quotient

$$\frac{a}{A} \div \frac{V}{V-e}.$$

It adds a great deal to the power of the investigator in finding out the facts if he has at hand an oscillograph with which to project the wave-form of the currents and electromotive forces under observation.